OR23 Hamburg

International Conference on Operations Research 2023

Decision Support & Choice-Based Analytics for a Disruptive World

Technical Program

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Plenary Speakers

Nils Kemme

HPC Hamburg Port Consulting

Out of the Box Thinking -
Real Life OR Applications for Container Terminals

Dr. Nils Kemme is Managing Director and port operations consultant at HPC Hamburg Port Consulting GmbH. He has more than fifteen years of experience and extensive knowledge in the field of planning, realizing and optimizing ports and intermodal facilities. In 2006, he started his career in the port industry with the optimization of the AGV-system at the Container Terminal Altenwerder in Hamburg, Germany. Thereafter, he joined HPC for the first time in January 2007, where he coordinated a major expansion program for a brownfield container terminal in Hamburg. In 2012, he rejoined HPC after four years as researcher and lecturer at the University of Hamburg, where he specialized in simulation-based planning and optimization of container terminals and earned his PhD degree in Operations Research. Since 2019, Nils Kemme is a partner at HPC and in 2021 he has been appointed as Managing Director. As such, he is a renowned speaker at international events of the port and transport industry and has published several books and articles in this area.

Huseyin Topaloglu

Cornell University

Incorporating Discrete Choice Models into Operations Management Models

Huseyin Topaloglu is the Howard and Eleanor Morgan Professor in the School of Operations Research and Information Engineering at Cornell Tech. He got his B.Sc. in Industrial Engineering from Bogazici University of Turkey and his Ph.D. in Operations Research and Financial Engineering from Princeton University. He has been a faculty member at the School of Operations Research and Information Engineering since 2002. He is currently serving as the Program Director for the Master of Engineering Program in Operations Research and Information Engineering at Cornell Tech. Professor Topaloglu works on large-scale stochastic optimization problems that arise in areas such as revenue management, inventory control, transportation logistics, and supply chain management. He is the department editor for Revenue Management Department of Product and Operations Management Journal. He serves as an associate editor for the journals Management Science, Mathematical Programming C, Naval Research Logistics, Operations Research, Transportation Science, IIE Transactions, and Surveys in Operations Research and Management Science.

Semi-Plenary Speakers

Sally Brailsford

Southhampton Business School

Improving emergency care using a new approach to generic simulation modelling

Professor Sally Brailsford is Professor of Management Science within Southampton Business School at the University of Southampton. Sally obtained a BSc in Mathematics from Kings College London, and then worked for several years as a nurse in the NHS before obtaining an MSc and then a PhD in Operational Research from Southampton. Her research is in the area of healthcare simulation modelling: to evaluate treatments and screening programmes, or to redesign and improve service delivery. Sally has worked for over 30 years in many different disease fields including diabetes, cancer, mental health and HIV/AIDS, in addition to emergency care and end-of-life care. From 2012-15 she was Vice-President 1 of EURO, the Association of European OR Societies. From 2010-19 she was Coordinator of the EURO Working Group on OR Applied to Health Services (ORAHS) and was a founding Editor-in-Chief of the UK OR Society's journal Health Systems. She is the only person ever to have won the OR Society's Goodeve Medal three times: in 2004 for modelling emergency healthcare services in Nottingham, in 2006 for modelling chlamydia infection, and in 2015 for modelling the supply and demand for dental care in Sri Lanka.

Ana Barbosa-Póvoa

Instituto Superior Técnico

Sustainable Supply Chain Management

Ana Barbosa-Póvoa is a Full Professor in Operations and Logistics, at the Engineering and Management Department of Instituto Superior Técnico (IST), University of Lisbon. She holds a PhD from the Imperial College of Science Technology and Medicine and her research focus is on developing a comprehensive understanding of complex problems in supply chains and operations management, supported by novel and sound engineering systems models and techniques. Sustainability, resilience, uncertainty and risk in the design and planning of supply chains are among the main research-addressed domains. Ana has created and coordinates the research group in Operations Management and Logistics and Supply Chain Management (OpLog) at the Centre for Management Studies of IST. She has a large experience of in supervision and has been awarded with several research grants. Her research has led to several national and international awards having twice received the honor of being considered the best researcher in Industrial Management at the University of Lisbon. She is an editor of the Computers and Chemical Engineering Journal and a member of several editorial boards, namely the European Journal of Operational Research, the International Journal of Production Economics, TOP, and Operations Research Perspectives. She is one of the Vice Presidents of the EURO, European Association of Operational Research Society; a founder member of the Euro Working Group in Sustainable Supply Chains of the European Association of Operational Research – where she is currently part of the coordination team, and a member of the Euro Working Group on Retail, and the Euro Working Group on Location and Analysis. She serves in the events sub-committee of the EURO WISDOM Forum.

Joanna Józefowska

Poznan University of Technology

Models for just-in-time scheduling

Full Professor at the Institute of Computing Science, Poznan University of Technology, Graduated in Mathematics at Adam Mickiewicz University and Management Engineering at PUT, Ph.D. and habilitation at the Faculty of Electrical Engineering, PUT. Post-doc at Memorial University, Newfoundland Canada, visiting professor at Brandenburg University of Technology and University of Siegen. In 2012-2020 Vice-rector for Research at PUT. Since 2020 the first Vice-President of the Association of European Operational Research Societies (EURO), since 2018 Coordinator of the EURO WG on Project Management and Scheduling (together with Erik Demeulemeester – KU Leuven). Major research areas: scheduling (project, machine, production), artificial intelligence, in particular knowledge representation systems. Author and co-author of 7 books and more than 100 papers in major professional journals and conference proceedings.

Christoph Weber

University Duisburg-Essen

OR-models for the energy transition – coping with uncertainty and heterogeneity

Christoph Weber is professor for Energy Economics at the University Duisburg-Essen and is particularly interested in applied modelling for decision support under uncertainty. He has published on a broad range of topics related to energy markets and the decarbonization of the energy system.

Sven Müller

RWTH Aachen

Locational choices and decisions: choice-based facility location planning

Sven Müller is professor for Data and Business Analytics at the RWTH Aachen University, Germany. He holds a venia legendi in Business Administration from Hamburg University, a PhD in Transport Economics from University of Technology Dresden (summa cum laude), and a master's degree in Economic Geography from RWTH Aachen University. Prior to his current position, Sven held various positions as associate or full professor at Otto-von-Guericke-University Magdeburg, European University Viadrina, and University of Applied Sciences Karlsruhe. His research interests are at the intersection of prescriptive and predictive analytics with applications to assortment optimization, revenue management, facility location, transportation, energy, and health care.

Max Klimm

TU Berlin

Information design for congested networks

Max Klimm is an Assistant Professor for Discrete Optimization at the Technische Universität Berlin. He is interested in the analysis and optimization of multi-agent systems in traffic, telecommunications, and economics using tools from mathematical optimization, game theory, and mechanism design. Before joining TU Berlin in 2020, he was an Assistant Professor for Operations Research at the Humboldt-Universität zu Berlin. From 2014 to 2016, he was the head of the Junior Research Group for Optimization under Uncertainty at the Einstein-Center for Mathematics. He received his PhD in 2012 in Mathematics from Technische Universität Berlin.

David Manlove

University of Glasgow

Models and Algorithms for Kidney Exchange

Ana Barbosa-Póvoa is a Full Professor in Operations and Logistics, at the Engineering and Management Department of Instituto Superior Técnico (IST), University of Lisbon. She holds a PhD from the Imperial College of Science Technology and Medicine and her research focus is on developing a comprehensive understanding of complex problems in supply chains and operations management, supported by novel and sound engineering systems models and techniques. Sustainability, resilience, uncertainty and risk in the design and planning of supply chains are among the main research-addressed domains. Ana has created and coordinates the research group in Operations Management and Logistics and Supply Chain Management (OpLog) at the Centre for Management Studies of IST. She has a large experience of in supervision and has been awarded with several research grants. Her research has led to several national and international awards having twice received the honor of being considered the best researcher in Industrial Management at the University of Lisbon. She is an editor of the Computers and Chemical Engineering Journal and a member of several editorial boards, namely the European Journal of Operational Research, the International Journal of Production Economics, TOP, and Operations Research Perspectives. She is one of the Vice Presidents of the EURO, European Association of Operational Research Society; a founder member of the Euro Working Group in Sustainable Supply Chains of the European Association of Operational Research – where she is currently part of the coordination team, and a member of the Euro Working Group on Retail, and the Euro Working Group on Location and Analysis. She serves in the events sub-committee of the EURO WISDOM Forum.

Wednesday, 8:30-10:00

■ WA-01

Wednesday, 8:30-10:00 - ESA A

Opening Ceremony & GOR Scientific Award

Stream: PC Stream
Plenary session
Chair: *Guido Voigt*

Wednesday, 10:30-12:00

■ WB-02

Wednesday, 10:30-12:00 - ESA B

Decision Support in Sales and Logistics

Stream: Decision Analysis and Support
Invited session
Chair: *Michael Höck*

1 - Techno-economic assessment of hydrogen transport routes to Germany
Nicolas Wolf

Green hydrogen plays a crucial role on the way to decarbonizing Germany's energy supply and industry. Its potential as a climate-neutral fuel and flexibilization option for the energy system opens up a range of future applications. Current forecasts predict a German green hydrogen demand in 2050 that will exceed the domestic production potential. Therefore, supply chains to import green hydrogen from countries with advantageous conditions for efficient green hydrogen production are being discussed by German policy makers. This study conducts a techno-economic analysis of hydrogen transport routes to Germany for the year 2050, evaluating the transportation forms of compressed gaseous hydrogen, liquified hydrogen, and Liquid Organic Hydrogen Carriers. Different transport routes from Norway, Spain, Morocco and Australia to Germany are designed. In addition to considering technical transport requirements, the costs of each supply chain are calculated. The results show that the transport of compressed gaseous hydrogen via pipelines to Germany is by far the cheapest option, with an import from Norway having the lowest costs, followed by Spain and Morocco. Ship transport of liquefied hydrogen as well as via Liquid Organic Hydrogen Carriers is not competitive compared to pipeline transport. Therefore, based on transport costs, an import of green hydrogen to Germany should primarily be realized via pipelines from Norway, alternatively from Spain and Morocco. An import from Australia should not be considered in terms of cost, due to the sole shipping possibility.

2 - Energy Supply Chain Resilience and Sustainability Practices: Insights on Sourcing and Pricing Strategies
Hamed Rajabzadeh, Marcus Wiens

The energy supply chain is critical for meeting the increasing global energy demand. However, disruptions in the energy supply chain can have dramatic effects on various stakeholders, including manufacturers, consumers, and the environment. This study proposes a game-theoretic model integrating renewable and fossil fuel power plants to increase supply chain resilience. The manufacturer benefits from a renewable power plant as the main supplier and a fossil fuel power plant as backup. Two sourcing strategies are considered dependent on disruption probability: (1) single sourcing from renewable power plant, and (2) dual sourcing from both renewable and fossil fuel power plants. To analyze the decision-making process in the uncertain environment of the energy supply chain, a game theoretic approach provides the appropriate framework to analyze the strategic interactions between different players in a complex system, such as the interactions between the renewable and fossil fuel power plants and the manufacturer in this study. Based on the two sourcing options, we analyze the strategic scope for different levels of collaboration between power plants, capturing interactions, ordering decisions, and pricing strategies. This study contributes to the literature, particularly in the areas of resilience and sustainability in the energy supply chain. By proposing a novel energy supply chain model that integrates renewable and fossil fuel power plants, considering different sourcing strategies and collaboration scenarios, and analyzing the decision-making process from a game-theoretic perspective, this study offers insights into how to overcome energy supply risk by supply chain design and collaboration.

3 - Multi-Objective Network Optimization in Disaster Relief Logistics
Katharina Eberhardt, Florian Kaiser, Frank Schultmann

Last-mile distribution is one of the most critical parts of a disaster relief operation. Various uncertainties, such as infrastructure conditions,

resource availability, and fluctuating beneficiary demand, render last-mile distribution challenging in disaster relief operations. The need to balance critical performance criteria like response time, meeting demand, and cost-effectiveness further complicates the task. The occurrence of disasters cannot be controlled, and the magnitude is often challenging to assess. Therefore, we formulate a scenario-based multi-objective optimization model that integrates pre-positioning, allocation, and distribution of relief supplies extending the general form of a covering location problem. The proposed model aims to minimize underlying logistics costs while maximizing demand coverage. Using a set of disruption scenarios, the model allows decision-makers to identify optimal network solutions to address the risk of disruptions. We provide an empirical case study of the public authorities' emergency food storage strategy in Germany to illustrate the potential applicability of the model and provide implications for decision-makers in a real-world setting. Also, we conduct a sensitivity analysis focusing on the impact of varying stockpile capacities, single-site outages, and limited transportation capacities on the objective value. The results show that the stockpiling strategy needs to be consistent with the optimal number of depots and inventory based on minimizing costs and maximizing demand satisfaction. As such, the model provides decision support for public authorities to determine an efficient stockpiling strategy and distribution network and provides recommendations for increased resilience.

4 - A decision support for CO2-oriented tactical sales planning for manufacturers of light commercial vehicles
Till Uhlich, Karsten Kieckhäfer

Due to increasingly stringent CO2 fleet emission regulations in the EU, manufacturers of light commercial vehicles must trade off contribution margins and CO2 fleet emissions when deciding on the sales volume of each possible vehicle variant in tactical sales planning. Given the wide variety of vehicle models, engine-gearbox combinations, registration types, trim lines, and customer-specific configuration options available, this decision can be considered a complex undertaking. We strive to provide decision support by developing a mixed-integer optimization model that allows to derive optimal sales plans from both a financial and an environmental perspective. To this end, we consider alternative objective functions with and without taking into account the CO2 fleet emissions and possible penalties for non-compliance with the CO2 regulation. Moreover, important constraints such as available production and logistics capacities as well as the maximum demand are regarded. A special feature is the consideration of several registration types (passenger cars, light commercial vehicles, camper vans, and special purpose vehicles), which are affected by the CO2 regulation in different ways. Based on the optimization model, we analyze how alternative sales plans on the level of models, variants, registration types, and equipment options with similar contribution margins can lead to very different outcomes with respect to CO2 fleet emissions and vice versa. This way, we illustrate the levers of tactical sales planning in the context of CO2 management at light commercial vehicle manufacturers, a field largely neglected in the extensive body of literature on CO2 emission reduction in the automotive industry so far.

■ WB-03

Wednesday, 10:30-12:00 - WiWi A, VMP5

Operational Efficiency in Logistics: Integration, Tariffs, and Tour Coverage

Stream: Logistics
Invited session
Chair: *Finn Meissner*

1 - The Traveling Purchaser Problem with Zone-Based Tariffs
Finn Meissner

The Traveling Purchaser Problem (TPP) serves as a model for a multitude of transportation and procurement issues. This well-known generalization of the Traveling Salesman Problem describes various applications where the costs for tours and procurement are interwoven. In the basic model, a decision-maker buys products from different markets while balancing the prices of each market together with the tour costs from visiting them. However, in many real-world applications, other specific circumstances limit or modify the decision space. Many TPP variants have been developed to reflect these circumstances of different problems accurately. To the best of our knowledge, one variant that has not been investigated yet describes the problem of additional tariffs payable when a truck enters a particular area to visit markets. This case describes the real-world situation as it is often found, e.g., near country borders in areas with location-dependent tolls. A subset of markets shares an extra fee as soon as one of them is visited. This paper explores this new variant with zone-based tariffs (TPP-ZBT). The model is set up and then examined in detail to understand the special characteristics of the problem compared to the basic variant. Further, the structure of the solutions is examined to get deeper insights into this design.

2 - The integration of order picking and vehicle routing operations in a dynamic setting
Ruben D'Haen, Kris Braekers, Katrien Ramaekers, Claudia Archetti

E-commerce experienced tremendous growth over the past decade. Order volumes have increased rapidly, with an associated increase in competition between e-commerce companies. Furthermore, customers expect very short delivery times, sometimes within a couple of hours. In order to handle these increased order volumes with short delivery deadlines competitively, companies need to schedule their operations in an efficient manner.

Customer orders have to be picked in a warehouse first, followed by delivery to the customer's location. These two processes are traditionally handled sequentially. In the sequential approach, a predefined picking deadline is set for every order, based on a simple rule of thumb. Both order picking and delivery are then scheduled to respect these order deadlines. To improve the order handling process, order picking and delivery can be scheduled in an integrated manner. In the integrated approach, there is no predefined picking deadline and order picking and delivery are scheduled at the same time. By removing the fixed picking deadline for all orders and allocating the time for the order picking and delivery processes in an intelligent way for every order individually, large efficiency improvements are possible.

Although previous research already looked into the integration of order picking and delivery, the dynamic arrival of new orders has not been considered yet. Therefore, we propose multiple metaheuristic optimisation algorithms to solve this integrated order picking and delivery problem while accounting for dynamic order arrivals. The performance of the different algorithms is studied in a series of numerical experiments, leading to a better understanding of the integrated order picking and vehicle routing problem.

3 - Variants and applications of the Covering Tour Problem: A literature review
Fatma Ben Amor, Manel Kammoun, Taicir Loukil

The Covering Tour Problem (CTP) was presented as a generalization of the Traveling Salesman Problem in which not all nodes must be visited. In this problem, the non-visited locations must be covered by the nearest location scheduled in the tour. Hence the introduction of the notion of the coverage. The main concept of the CTP is that some nodes must be visited by the vehicles whereas some other nodes have to be covered. If a node is located within a predetermined covering distance of its next visited node, it is said to be covered. This problem considers different types of locations: some nodes must be visited noted as the set T through the set V which contains the prospective nodes, whereas W contains the set of locations which must be covered. The main objective of the CTP is to find a minimum-length Hamiltonian cycle. Recently, this problem became one of the most important problems in different fields such as supply chain management, logistics, combinatorial optimization, and, in general, of operational research. The interest in this subject has lately increased, both theoretically and practically. Multiple researches in these previous years have been interested to the Covering tour problems for real-life applications, such as, humanitarian logistics, regional development, urban patrolling, and health-care management. To the best of our knowledge, no work has considered reviewing the covering tour problem, it's formulation and its potential applications. For this reason, we will introduce in this work, the CTP and its different variants studied recently. The main objective is to examine the literature already in existence to highlight the studies that have already been done and to identify any gaps and promising areas for further study.

■ WB-04

Wednesday, 10:30-12:00 - WiWi B1, VMP5

Navigating Logistics Challenges: Insights into RoRo Vessels, Route Planning, and Dynamic Demands

Stream: Logistics
Invited session
Chair: *Barbara Himstedt*

1 - Combining multiple delivery systems for urban logistics by ALNS-based route planning

Barbara Himstedt, Frank Meisel

For decades, diesel-powered delivery vans were the only means of parcel delivery. With increasing attention to the externalities they cause, parcel delivery service providers are expected to make the switch. Innovative and more environmentally friendly delivery vehicles such as cargo bikes, delivery robots, or drones are supposed to replace the old technology. But moving to just one of these delivery systems is often not a viable option, due to a lack of prerequisites at the customer's site or simply too large a package size. However, a combination of multiple delivery systems to supplement traditional delivery could be a solution. In this talk, we address a variant of the two-echelon vehicle routing problem arising in city logistics. To cope with the characteristics of a wide variety of delivery vehicles, it involves not only the deployment of multiple vehicle types at the second echelon, but also direct delivery by first-echelon vehicles, transfer of second-echelon vehicles, and the possibility to pick up additional parcels during a tour. In addition, the applicable delivery systems can be set up individually for each customer. We propose an Adaptive Large Neighborhood Search (ALNS) heuristic that incorporates problem-specific local search and destroy operators. Extensive experiments on realistic delivery areas in the city of Hamburg, Germany, demonstrate the effectiveness of the algorithm when considering different fleet compositions and instance sizes. Preliminary results indicate that combining delivery systems can generate significant cost savings compared to traditional van delivery and that customer preferences have a significant impact on the optimal fleet composition.

2 - A deterministic continuous-time model for dual cycling in loading and unloading RoRo vessels

Teresa Marquardt, Arne Heinold, Catherine Cleophas, Frank Meisel

Roll-on Roll-off (RoRo) vessels are a popular mode of transport in short-sea shipping, providing a fast and convenient way to transport rolling cargo such as trailers. To enhance the efficiency and sustainability of RoRo shipping, optimizing the unloading and loading process of RoRo vessels is crucial. One key way to this is dual cycling, where tug masters simultaneously load and unload the vessel. This reduces the overall processing time and the vessel's turnaround time. As a result, the vessel spends less time in port and has more time to travel to the destination; this induces slower sailing and reduced emissions. Our study extends the RoRo Dual Cycling Problem (RRDCP) by incorporating a continuous time horizon and considering both unaccompanied and accompanied cargo. These model extensions enable a more detailed differentiation of processing times across cargo units. Further, it makes solutions more applicable in practice, as RoRo vessels often ship both unaccompanied and accompanied cargo. Solving the RRDCP means generating an efficient schedule that sequences cargo units and assigns unaccompanied units to tug masters. Given a stowage plan, the problem is constrained by physical restrictions, which lead to precedence constraints across cargo units. For instance, units closer to the ramp connecting the vessel to the quay must be unloaded before units in the back. As the mathematical complexity of the mixed-integer linear programming model hinders solving the problem to optimality for instances of realistic size, we provide and evaluate a metaheuristic based on a genetic algorithm.

3 - The stochastic inventory routing problem with dynamic demands and intra-day depletion

Emilio Jose Alarcon Ortega, Sebastian Malicki, Karl Doerner, Stefan Minner

Vehicle routing and inventory management play an increasingly important role in the supply chain of a wide range of businesses. This is especially remarkable for companies that manage products sensitive to characteristics such as perishability or uncertain demands. Vendor managed inventory is an effective strategy where a central supplier manages simultaneously the inventory and routing of a set of retailers. The problem we present in this article aims at reducing the overall routing and inventory costs considering the stochastic and dynamic nature of demands. We model the problem as a finite-horizon stochastic dynamic program where each period during the planning horizon is divided into sub-periods with distinct demand distributions. The modeled characteristics include routing, holding and stock-out costs, inventory and vehicle capacities, and delivery time windows. Inventory calculations are performed at the end of each subperiod, to account for the possible lost sales that may occur during the period. Furthermore, at the beginning or each period, the routes, replenishment quantities, and sub-periods in which each customer is visited, are planned and cannot be altered throughout the period. To solve this problem, we propose an iterative look-ahead algorithm that combines an adaptive large neighborhood search with a policy learning process for the replenishment decisions. Then, we evaluate the efficiency of the proposed algorithm by comparing the obtained results against benchmark sequential decision algorithms. Computational experiments show the effectiveness of the proposed algorithm when considering different instance configurations. Furthemore, considering intra-day consumption of goods helps the central supplier reduce the overall costs.

4 - Design and Implementation of a Data-Driven Instance Generator for Loading and Unloading RoRo-Ships

Catherine Cleophas, Arne Heinold, Teresa Marquardt, Frank Meisel

The process of loading and unloading RoRo (roll-on roll-off) -ships is a main driver for productivity in small- and mid-size harbors in the Baltic Sea. The process differs from the classical loading and unloading of large container ships due to uncertainty regarding the stowage plan and regarding travel times between quay areas. Furthermore, shippers can load both accompanied trailers and unaccompanied cargo. Tugs handle the latter, allocating them to areas on board or within the quay. Therefore, the problem of loading and unloading RoRo-ships corresponds to a pick-up-and-delivery problem with uncertainty, single capacity, and precedence constraints. This talk presents the design of a software system for generating realistic problem instances from a set of given parameters, as may be inspired by real-world situations. Consequently, the resulting instances are of a general nature and exceed the limited scope of specific, empirically observed problem instances. The generator can be configured according to problem-specific layouts and input data like the cargo types, stowage plan, size of the quay areas and vessel, and distribution of tug-specific travel times. Each thus generated instance represents a scenario in which the RoRo-ship arrives at the harbor to be loaded/unloaded. Such instances are viable inputs in optimization approaches requiring lots of input data like approximate dynamic programming or simulation-based optimization. However, the related input data is usually not publicly available. To close this gap through the proposed system, we further present an implementation in Python, publicly available via Git. We also provide an overview of benchmark instances based on data collected in the Port of Kiel, which are publicly available as XML-files.

■ WB-06

Wednesday, 10:30-12:00 - ESA C

Production management

Stream: Supply Chain Management
Invited session
Chair: *Hartmut Stadtler*

1 - Resolving the curse of poor data quality: Optimization perspective on data collection and validation

Alena Otto, Benedikt Finnah, Jochen Gönsch

Companies possess large quantities of poor-quality data. The validation of which is costly, especially if the required data accuracy is high. In this talk, we focus on a specific subset of such data which is common across many industries and areas of business – data on precedence relations between tasks. We formulate the Data Collection and Validation Problem (DCVP) that aims to improve the input data for some baseline planning problem. The initial data on precedence relations between tasks, which imposes hard constraints on the baseline problem, is partially incorrect. Restricted by the available time budget, an expert dynamically receives queries about specific data entries and corrects or validates them. Since relevant solutions for the baseline planning problem must be feasible, only precedence relations, whose absence have been confirmed by the expert, can be removed from the data set.

Thus, the DCVP is an online optimization problem which looks for an optimal policy (interview policy) of stating queries to the expert to maximize the (weighted) number of removed precedence relations within the available time budget. We analyze the properties of the DCVP formally, model the DCVP as a dynamic program, and suggest a customized least squares temporal difference algorithm LSTD. We prove theoretically and experimentally that data validation by experts can lead to significant savings for companies even if the available time budget is limited. Moreover, in extensive computational experiments, the designed LSTD interview policy considerably outperforms alternative ones. In a case study of a leading automobile manufacturer's assembly line, this policy substantially reduces the stations' idle time after selectively addressing only about 8% of the data entries.

2 - Stochastic Programming for Dynamic Design of Matrix Assembly Systems
Baturhan Bayraktar, Martin Grunow, Rainer Kolisch

Increasing uncertainty in product demand due to recent technological advancements affects the productivity of traditional assembly lines of original equipment manufacturers. Due to their easy reconfigurability in case of demand changes, matrix-shaped assembly layouts in which automated guided vehicles (AGVs) move products between the workstations placed in a grid arrangement are more frequently implemented by the layout designers. Our investigation focuses on the advantages of matrix assembly layouts under uncertain demand in a multi-period planning horizon. We develop a multi-stage stochastic programming technique for designing and adapting the matrix assembly layouts and utilize several realistic scenarios to represent the uncertainty of the demand. We first consider the station activation and task assignment decisions without future demand knowledge. Subsequently, the flows are allocated to different AGV routes after the demand is revealed. The objectives are to maximize the efficiency of the layouts and to minimize the expected number of reconfigurations. We formulate a lexicographic multi-objective mixed integer linear programming model to solve the problem. The experimental design evaluates the value of the stochastic solution for problem instances derived from the literature. Finally, we compare the reconfigurable matrix assembly layouts with mixed-model assembly lines.

3 - Increasing the productivity of a multi-stage biomanufacturing process using MDP modelling
Martin Grunow, Mirko Schömig

Biopharmaceuticals are drugs produced in a multi-stage biomanufacturing process. The use of living cells introduces multiple operational uncertainties into the system. Today, the manufacturing stages are often treated as independent entities operated with fixed process control strategies, neglecting the trade-off these decisions create across stages. Further, process monitoring data routinely collected to prove regulatory compliance of the process, are not used for operational decision-making. We formulate the multi-stage biomanufacturing process as an MDP and determine an integrated policy. We show the applicability of the policy for a typical biomanufacturing process, focussing on the implementation of the operations policy in practice.

4 - How to Generate a Small Set of Representative (Demand) Scenarios
Hartmut Stadtler

Scenario-based stochastic MIP-models have attracted many researchers in production and logistics due to its simplicity and flexibility in modeling (e.g. service level constraints). However, these MIP models incur a dilemma: While a large number of scenarios increase accuracy, it also increases computational efforts substantially.

We present a novel MIP-model that creates a relatively small set of (demand) scenarios that not only uses descriptive sampling for the periods' demands but also combines these demands period-by-period such that there is a good fit to the convoluted distributions in periods t= 1..T.

Besides the model formulation we also provide some computational test results for the normal distribution.

■ WB-07

Wednesday, 10:30-12:00 - ESA J

Optimal Control in Models with Regime Switching

Stream: Continuous and Global Optimization
Invited session
Chair: *Dmitry Gromov*

1 - Switch from Cooperative Regime to Competition or Confrontation in a Differential Game
Ekaterina Gromova, Ekaterina Marova

This research explores the dynamics of cooperation in a differential game, specifically analyzing the profitability of forming coalitions versus playing individually in a regime of competition or confrontation with other players. The benefits of entering a coalition are measured using the value of cooperation (VC) and normalized value of cooperation (NVC), while the strength of the coalition is characterized by the value of characteristic function constructed using four different methods. Additionally, the study introduces the value of confrontation (VCF) and normalized value of confrontation (NVCF), which can be calculated for individual players or coalitions.

The main idea behind the value of cooperation is to determine the potential loss incurred when rejecting cooperative solutions in favor of the Nash equilibrium solution. An acceptable relative amount of loss is set with the condition NVC < k, and if this inequality holds, cooperation may be abandoned. A similar problem can be formulated for coalitions, and a characteristic can be computed over time to detect when to deviate from cooperation, based on the condition NVC(t) < k. A similar characteristic as a function of time (value of confrontation) may also help to detect the time of switching from cooperation to a zero-sum game.

To validate these theoretical findings, the study applies them to a real-world scenario of pollution control involving three players.

This research was partially conducted while E. Gromova was with St. Petersburg State University and was funded by RFBR and DFG, project number 21-51-12007.

2 - Differential Game in Renewable Resources with Sliding Modes and Hybrid Limit Cycles
Thorsten Upmann

We explore a standard harvesting model with possible regime switching in the dynamics of the resource stock, where the growth rate of the stock changes in non-smooth nature at the threshold. Within this framework, we consider a non-cooperative game with n players (fisher). We show that thresholds of the state variable may bring about tipping points, and that these thresholds may result in equilibrium strategies where harvesting takes place on the boundary; in this case, the sliding mode may emerge as the equilibrium outcome under certain conditions. Also, we prove necessary conditions for the crossing hybrid limit cycle trajectory to the optimal outcome of the game. Lastly, we discuss environmental and policy implications of these novel types of dynamics.

3 - Optimal Experimentation in a Gaussian Environment
Stefan Behringer

In this paper I study an extension of the Keller Rady (1999) model of monopoly experimentation in a changing environment with two demands to infinitely many possible demands that follow a Gaussian process. Using dynamic Kalman-Bucy-Stratonovich filtering I show that the main economic intuitions are robust.

■ WB-08

Wednesday, 10:30-12:00 - ESA M

Inventory management

Stream: Supply Chain Management
Invited session
Chair: *Sonja Otten*

1 - Production-inventory system with perishable items
Sonja Otten, Ruslan Krenzler, Hans Daduna, Karsten Kruse

Production processes are usually investigated using models and methods from queueing theory. Control of warehouses and their optimization rely on models and methods from inventory theory. Both theories are fields of Operations Research (OR), but they comprise quite different methodologies and techniques. In classical OR these theories are often considered as disjoint research areas. Today's emergence of complex supply chains (=production-inventory networks) calls for integrated queueing-inventory models, which are the focus of our present research. We consider a supply chain consisting of a production system with an attached inventory with perishable raw material where the item of raw material that is in the production process and not in the inventory anymore cannot perish. Demand of customers arrives at the production system according to a Poisson process and is lost if the local inventory is depleted ("lost sales"). To satisfy a customer's demand a server at the production system needs raw material from the inventory. For the control of the inventory we use the base stock policy and the inventory is replenished by a supplier. We develop a Markov process model for this supply chain and prove that the stationary distribution has no product form. For the special case with base stock level equal to one, we obtain an explicit closed solution for the stationary distribution. However, for the system with base stock level greater than one an explicit expression of the complete stationary distribution is still an open problem. Therefore, we modify the system so that we get product form results and deal with the question "Can we use the product form results to obtain simple product form bounds for the system with unknown non-product form stationary distribution?".

2 - Evaluation of value-oriented inventory policies with fluctuating purchase prices

Philipp Erfurth, Matthias Gerhard Wichmann

In multi-period inventory management, decisions are made about procurement timing and procurement quantities as well as on the inventory control of goods. In order to strive for cost minimization, for B and C goods procurement companies typically apply inventory policies. These demand-driven decision-making policies consider a stochastic demand. A major assumption of most policies are constant purchase prices. Today, however, products and services are often subject to price fluctuations over time. This leads to two open questions. Firstly, it is unknown whether conventional inventory policies are economically advantageous in the presence of fluctuating purchase prices. Secondly, it is unknown how and to what extent value orientation might be incorporated in inventory policies. Both questions are analyzed by introducing and evaluating a simulation study with fluctuating purchase prices. In doing so, value-oriented aspects are identified in the literature and integrated into inventory policies as a basis for decision making. The study focuses on the development of inventory policies for goods with fluctuating prices and their performance compared to conventional inventory policies. The simulation is evaluated as a function of the level of demand and price fluctuation. It is shown that value-oriented extensions are advantageous in performance and robustness of the solution with increasing price fluctuation. These results call for further research on the efficient configuration of value-oriented inventory policies to procure and store economically when prices fluctuate.

3 - Finding a re-order point to secure a fill rate target for an inventory system with lost-sales using censored demand data

Christian Larsen, Johan Bjerre Bach Clausen

We study an (R,Q) inventory system where R is the re-order point and Q is the order size. There is a constant lead-time L for any replenishment order. We assume unfilled demand is lost. This is not an uncommon phenomenon in a retail setting. Often it is so that the order size Q is pre-determined, either by use of the EOQ formula or due to practical considerations, say, when ordering always order a full container load. We will demonstrate a method, based on repeated maximum likelihood estimations, that can compute a re-order point which secures a fill rate target, although that we initially only have a limited amount of data at hand and never are able observe the demand but only the sales, that is, the demand data are censored.

4 - Establishing humanitarian inventories under quantity, location, and time uncertainties

Baruch Keren, Yossi Hadad

An emergency incident will occur in the coming years, somewhere. Establishing an emergency or humanitarian inventory in advance is a response that can mitigate the effects of the expected incident. The problem is to preposition such inventory in the right location, with the right quantity and to do so at the right time—taking into account that the incident's location, timing, and magnitude may be random variables. This paper presents a model for the triple uncertainties inventory problem (location, timing, and quantity). It shows how the solution to this problem can be optimized analytically and numerically, even in cases where there is a statistical dependence between the random variables. One result of the model can be an immediate establishment of an emergency inventory with the optimal quantity and location; another can be a "wait and see" strategy with periodic updating of the model as newer information becomes available. The paper provides benchmark solutions to help decision-makers make wiser choices about the timing, location, and quantity of inventories positioned in anticipation of an emergency. The model is applicable, especially for disasters with a long mean time between occurrences (years), which usually motivate decision-makers to prefer the "wait and see" strategy.

■ WB-09

Wednesday, 10:30-12:00 - ESA O(st) 221

Optimization with nonsmooth or combinatorial structures

Stream: Continuous and Global Optimization
Invited session

Chair: *Alberto De Marchi*
Chair: *Matthias Gerdts*

1 - Solving mathematical programs with complementarity constraints in nonsmooth optimal control

Armin Nurkanovic

This talk presents a direct approach to solving optimal control problems with nonsmooth dynamical systems. In particular, we regard several classes of dynamic complementarity systems with different smoothness properties. We review the Finite Elements with Switch Detection (FESD) method, which, in contrast to standard time-stepping methods enables a high-accuracy time discretization of the initial optimal control problem. Sensitivities obtained via time-stepping methods are in general incorrect, whereas FESD also enables the computation of correct numerical sensitivities. We highlight some of the standard limitations of other standard methods to motivate the development of tailored methods. After the time discretization, we obtain a mathematical program with complementarity constraints (MPCC). MPCCS are degenerate nonsmooth nonlinear programs that violate standard constraint qualifications at all feasible points. We discuss some standard reformulation techniques and solution strategies used to solve MPCCs arising from discretized optimal control problems.

2 - Sensitivity analysis of the solution mapping for a large class of optimization problems

Matus Benko, Terry Rockafellar

In this talk, we focus on behavior of local solutions to finite-dimensional parameterized optimization problems in a very general setting. Lipschitzian stability of these solutions has been a crucial topic in optimization theory for decades and while it is understood fairly well - an abstract characterization has been available since the introduction of the particular perturbation scheme in 2000 by Levy, Poliquin, and Rockafellar - there are still many open questions. We propose a new interpretation of this characterization, which also enables us to derive a new sufficient condition for the Lipschitzian stability in case of the standard nonlinear programs. Moreover, thanks to the recent developments in variational analysis, we are able to compute the graphical derivative of the local solution mapping. We connect the graphical derivative with a solution of certain optimization subproblem defined via second subderivatives of the original objective function. Our ultimate goal, motivated by the desire to articulate solution dynamics via a one-sided differential equation, is to develop conditions ensuring that the solution mapping - single-valued and Lipschitz continuous, but nonsmooth - possesses one-sided directional derivatives. As this is an ongoing project, sometimes we provide only partial answers and we also propose some related open questions.

3 - Integer Linear Programs Arising from a Trust-Region Algorithm for Integer Optimal Control with Total Variation Regularization

Marvin Severitt, Paul Manns

We consider a MIOCP with a total variation regularization in the objective, which may be interpreted as a penalization of switching costs

between different control modes. To obtain the solution of the control problems we use a trust-region algorithm from which integer linear programs arise as discretizations of the subproblems. In the one-dimensional case a graph-based approach is used to solve the discrete subproblems and we discuss how the information obtained can be extended to the two-dimensional case.

4 - Penalty Interior Proximal Approach for Constrained Nonsmooth Nonconvex Problems

Alberto De Marchi

We address constrained structured optimization problems, which consist in minimizing the sum of a smooth and a merely lower semicontinuous function, subject to constraints described by a smooth function and a closed set. Without any convexity assumptions, we present and discuss flexible algorithms that combine penalty, interior point, and proximal gradient schemes. While traditional interior point methods do not handle nonsmooth objective functions and proximal algorithms cannot cope with complicated constraints, their combined usage is shown to successfully compensate the respective shortcomings. We provide a theoretical characterization of the algorithm and its asymptotic properties, deriving convergence results for fully nonconvex problems. Our interior proximal gradient algorithm benefits from warm starting, generates strictly feasible iterates with decreasing objective value, and returns after finitely many iterations a primal-dual pair approximately satisfying suitable optimality conditions. To overcome some practical limitations, an infeasible method is obtained by including an exact penalty term. Removing the need for strict feasibility along the iterates, the penalty approach benefits from accelerated solvers for the subproblems, as indicated by some illustrative numerical results.

■ WB-11

Wednesday, 10:30-12:00 - ESA H

Agent-based Modeling for Energy Economics and Energy Policy I

Stream: Energy and Environment
Invited session
Chair: *Florian Zimmermann*

1 - Energy systems analysis considering cross-border electricity trading: Coupling day-ahead markets in an agent-based electricity market model

Felix Nitsch, Aboubakr Achraf El Ghazi

Cross-border electricity trading can provide efficient allocation of power generation and demand, while also addressing the variability of renewable energy sources. In order to fully enable cross-border electricity trading, closer coupling of national electricity markets is essential. In this regard, we present a new day-ahead market coupling mechanism as part of AMIRIS, an open agent-based market model for investigating renewable and integrated energy systems.

The proposed approach looks as follows: Traders can either sell power generation capacities (e.g. conventional power plants, renewables, flexibility options) or ask for supply capacities when participating on the national, respectively market-zone specific day-ahead markets. Then, these bids and asks are forwarded to a central market coupling agent, which aims to maximize overall welfare by efficiently dispatching cross-border demands. At all times, the algorithm considers available transfer capacities between participating markets. Our algorithm guarantees correctness and termination within tolerance parameters, utilizing two criteria: (1) shifting only the minimal-effective-load at a time and (2) processing the most-effective-pair of all possible combinations first. The simulation is executed using the framework FAME.

Our implementation of the proposed mechanism is demonstrated in a case study, which illustrates the potential impact of cross-border electricity trading. This case study serves as a proof-of-concept for the practical application of our approach, which is soon to be published as a fully open-source feature of AMIRIS. Although the approach was developed for cross-border electricity trade, it is also suitable for assessments of smaller market zone (e.g. nodal pricing).

2 - Einfluss verschiedener Wetterjahre auf die Investitionsentscheidungen in agentenbasierten Strommarktmodellen

Thorsten Weiskopf, Florian Zimmermann, Emil Kraft

Agentenbasierte Strommarktmodelle werden vielfach eingesetzt, um die Entwicklung des Strommarkts und Energiesystems explorativ zu untersuchen. Häufig werden hierbei auf Basis von Eingangszeitreihen die Investitions- und Dispatch-Entscheidungen von konventionellen Kraftwerken, wie Gas- oder Kohlekraftwerke, und Speichertechnologien nachgebildet . Modelle wie PowerACE und AMIRIS nutzen Brennstoffpreisreihe, Last, Erneuerbaren-Energien (EE)-Erzeugung und Investitionsoptionen sowie den bestehenden Kraftwerkspark als Eingangsdaten. Die zu Grunde gelegte Last und EE-Erzeugung sind hierbei stark vom jeweiligen Wetterjahr, auf denen sie basieren, abhängig. Zum einen ist das Wind- und Strahlungsdargebot als auch der Wärme- und Kältebedarf, welche einen starken Einfluss auf den Strombedarf haben, jedes Jahr unterschiedlich, gleichzeitig führen technologische Entwicklungen dazu, dass eine reine Skalierung historischer Erzeugung zukünftige EE-Erzeugung systematisch unterschätzt. Es soll untersucht werden, ob die Verwendung von nur einem Wetterjahr dazu führt, dass, insbesondere bei Betrachtungszeiträumen von mehreren Jahrzehnten, es beim Vergleich zwischen verschiedenen Wetterjahren zu erheblichen Unterschieden in den Simulationsergebnissen , sowohl bei den Investitionen als auch bei den Marktpreisen, kommt. Ziel ist es die Unsicherheiten in Bezug auf EE-Erzeugung und Stromnachfrage im Agentenverhalten abzubilden. In Rahmen dieser Arbeit soll diese Unsicherheit in den Ergebnissen agentenbasierter Modelle, am Beispiel PowerACE, quantifiziert werden und dargelegt werden, ob die Verwendung von mehreren Wetterjahren oder die Nutzung synthetische Wetterjahren, also eine Kombination verschiedener Wetterjahre auf Erzeugungs- und Nachfrageseite, hier einen Vorteil bieten.

3 - Market equilibria of prosumers under market power: Analysis of combined oligopoly and oligopsony in electricity markets

Yi Wan, Martin Densing

The development of flexible energy resources, such as battery and P2X technologies, increases the flexibility of possible behavior of large players in energy markets. We consider the equilibrium bidding strategy of a large player who produces and consumes energy under capacity constraints on an electricity market. The analysis comprises a comparison to a combined duopoly and duopsony, in which the player is separated into a producer and a consumer, who both can exercise market power. Both Cournot and Stackelberg behavior of the producer and of the consumer are considered, and we consider also the reduction of market power by conjectural variations. In a case study using a numerical, technically-detailed electricity market model of the Central Western European region, we exemplify such dynamic strategies of price-making prosumers. We evaluate results with respect to key factors, including capacities constraints, generation cost and market prices. The findings suggest that the type of vertical integration of generation and consumption technologies has significant impacts and should be taken into account for a successful market design of consumption technologies (e.g. electrolysers for hydrogen technologies) for the energy transition.

4 - Predicting Fluid Interface Instability in Energy Systems for Sustainable Energy Transition

Thi Thai Le, Milena Petkovic

The ongoing energy transition demands sustainable and efficient energy production and consumption, where fluid interface stability's role in enhancing energy transition processes' efficiency is critical. Due to the coexistence of different gases in underground storage, this work explores the interface stability's impact on energy storage, specifically during the injection and withdrawal of gases such as hydrogen and natural gas. A new approach of combing simulation and time series analysis is used to predict instability modes in energy systems accurately. Our simulation is based on a 2D Navier-Stokes equation, solved using a finite volume method with a staggered grid. The solution is validated by comparing them to experimental data and analytical solutions, accurately predicting the instability's behavior. We use time series analysis and state-of-the-art regime-switching methods to identify critical features of the interface dynamics, providing crucial insights into system optimization and design. Our results can support the sustainable and efficient energy transition, offering a novel and effective means of predicting and optimizing fluid interface stability for improved energy system performance.

■ WB-12

Wednesday, 10:30-12:00 - ESA K

GOR PhD Thesis Awards 2023

Stream: PC Stream
Award Competition session
Chair: *Jutta Geldermann*

1 - Balanced Electric Vehicle Charging under Uncertainty: From User-Centric to System-Centric Approaches

Marianne Guillet

Electric vehicles (EVs) are an essential lever for decarbonizing the transportation sector. However, many drivers remain reluctant to purchase an EV as they do not trust the public charging infrastructure, due to charging station congestion risks and unreliable charging station availability. This thesis contributes novel models and solution methods, that aim to reliably help EV drivers find a free public charging station in the presence of uncertainties. From a short-term user perspective, the objective is to provide reliable in-car guidance instructions that explicitly account for charging station availability uncertainty. In a single-agent setting, an algorithmic framework composed of a rollout and a labeling algorithm can save up to 44% of a driver's search time. In a multi-agent setting, efficient driver coordination strategies through information-sharing and charging requests centralization can decrease the multi-agent search cost by up to 38%, compared to uncoordinated greedy searches. From a long-term perspective, the objective is to avoid public charging station utilization conflicts of drivers that get guidance instructions through self-interested navigation platforms. A mechanism design approach allows gearing the behavior of such platforms towards an outcome that benefits all EV drivers, by decreasing the total cost by up to 52% in an offline setting and by up to 42% in an online setting.

2 - Ordinal Costs in Multi-objective Combinatorial Optimization

Julia Sudhoff

Ordinal costs model the quality of objects whenever numerical values are not appropriate. As an example the safety of a street for a cyclist can be ranked in ordered categories, like, e.g., safe (bike lane), medium safe (slow traffic) and unsafe (busy street). Other examples for ordinal costs are quality, sustainability and rankings of olympic medals. In this talk, we provide a general modelling framework for combinatorial optimization problems with ordinal costs. We analyze ordinal orderings and cones and interrelate ordinal problems to associated multiobjective problems. The theoretical analysis is complemented by the development of generic as well as problem specific solution algorithms. Ordinal combinatorial optimization problems can be interpreted as a special case of multiobjective combinatorial optimization problems which are, in general, notoriously hard to solve. Nevertheless, the special problem structure supports tailored algorithms. For the special case of matroid problems with ordinal costs a polynomial time algorithm based on matroid intersection is suggested. An even faster algorithm is proposed for matroid problems with a real-valued and a binary objective function. The algorithm is very efficient as it exploits the connectedness of the efficient set and hence, it needs only a linear number of iterations.

3 - Mathematical Programming for Stable Control and Safe Operation of Gas Transport Networks

Kai Hoppmann-Baum

In 2022, after successful careers in virology and as head coaches of the national football team, Germany witnessed the rise of 83 million self-proclaimed experts in the energy sector, with a particular emphasis on natural gas and its transport. Indeed, due to the fight against climate change and ongoing geopolitical events, gas transport network operators currently face novel and complex challenges. The presented thesis addresses several associated planning problems and presents mathematical programming-based solution approaches. First, we introduce a decision support system for ensuring stable transient network control. Its core comprises a tri-level mixed-integer program (MIP) that quickly and reliably determines highquality control measures for a real-world, large-scale natural gas network. Anticipating future use cases, we adapt the algorithmic approach and demonstrate that the network can be repurposed for hydrogen transport if dedicated compressors and stricter rules for balancing supply and demand are implemented. However, control becomes more dynamic, and compression energy consumption increases. Knowing a network's technical limits is essential to ensure safe operation. We introduce two new optimization problems to identify severe transport scenarios. In their bilevel programming models, the leader selects supplies and demands that maximize the follower's transport effort. Solving the MIPs derived from their Karush-Kuhn-Tucker reformulations, we obtain convincing results in a case study. Finally, we discuss using uncrewed aerial vehicles for monitoring infrastructure and propose a MIP-based algorithm to optimize their routing. The latter considers the problem of finding minimum cycle partitions in directed graphs that satisfy vertex-induced length requirements.

4 - Demand Management in Shared Mobility Systems

Matthias Soppert

Shared mobility systems like car sharing and bike sharing have become an attractive and wide-spread type of urban mobility over the past decades. The biggest challenge regarding the profitable operation of such systems is the occurring dynamic imbalance between supply and demand, which stems from fluctuating demand patterns and spatially unbalanced vehicle movements. To counter these imbalances, the scientific literature so far has focused on the supply-sided control approach by means of active vehicle relocation. In this work, demand management is proposed as a cost-efficient alternative, in which the system's demand side is influenced through pricing and availability control. On the one hand, specific practice-relevant problems are addressed and solved. On the other hand, general modeling and solution approaches are developed, which can be transferred to related optimization problems for tactical and operational control of shared mobility systems. Extensive numerical studies, including case studies of Europe's largest car sharing company Share Now, demonstrate that demand management can be implemented successfully in shared mobility systems.

■ WB-13

Wednesday, 10:30-12:00 - ESA W(est) 121

Logistics

Stream: Mobility and Traffic
Invited session
Chair: *Pia Ammann*

1 - An Adaptive Large Neighborhood Search Algorithm for Two-Echelon Location Routing Problem with Mobile Depots and Time Synchronization

Banu Ulusoy Dereli, Gerhard Hiermann, Maximilian Schiffer

In city logistics, micro-depot locations provide significant savings compared to direct transportation of packages from one central depot. However, implementing only stationary micro-depots can be costly due to daily changes in customer locations in last-mile delivery. Therefore, there is a need to incorporate mobile depots in city logistics networks. Additionally, it is important to reduce the waiting times in micro-depots for on-time delivery and to carry out transportation with environmentally friendly vehicles that contribute to more sustainable logistics practices. Against this background, we focus on a two-echelon location routing problem with mobile depots and time synchronization between the echelons. We make decisions on the number and location of micro-depots, the first-level routes of the heterogeneous fleet from the central depot to the micro-depots, and the second-level routes of city freighters from the micro-depots to the customers. Our model i) considers the location of the stationary and mobile depots simultaneously and ii) allows direct transportation from the central depot to the customers. Our approach aims to minimize the total costs incurred by opening stationary and mobile depots, the transportation costs in both echelons, and vehicle usage costs. We formulate our approach as a mixed integer linear programming model and propose an adaptive large neighborhood search algorithm to solve large problem instances of realistic size. We test the performance of our mathematical model and solution algorithm on modified benchmark datasets frequently used in the literature.

2 - Generating diverse solutions for vehicle routing problems via reinforcement learning

André Hottung, Kevin Tierney

Deep reinforcement learning methods have shown significant promise at generating solutions to vehicle routing problems in a sequential decision process. At test time, these methods usually sample multiple solutions per instance from a trained model to search for high-quality solutions. However, it has been observed that trained models can suffer

from overconfidence in their actions during the sequential construction process which can lead to low solution variety and hence an impaired search performance. We evaluate existing techniques that allow to increase solution diversity and their impact on the overall search performance. Furthermore, we present a novel approach that significantly increases the solution diversity and evaluate it on the vehicle routing problem and the vehicle routing problem with time windows.

3 - Joint Truck and Driver Routing and Scheduling for Level-4-Automated Platoons
Pia Ammann, Szymon Albinski, Teodor Gabriel Crainic, Rainer Kolisch

Recent advances in automated driving technology gave rise to truck platooning, a form of shared transportation that allows multiple trucks to drive in close succession, connected through a data link. This technology promises a reduced fuel consumption and carbon footprint and, with increasing automation levels, additionally allows for significant labor cost reductions. In Level-4-automated or semi-autonomous platoons, only the leading truck must be operated by a human. Usually, trucks can form platoons for a major part of their routes, but some parts, such as the first and last mile, are still driven individually and hence require a human driver for each truck. With labor cost being a main cost driver in transportation, Level-4-automated platooning has the potential to revolutionize the trucking industry. However, new planning approaches are needed to utilize the savings Level-4-automated platoons offer. Specifically, trucks and drivers must be considered separate planning units, and drivers must be able to switch trucks en route to utilize their working time efficiently. Thus, interdependencies exist between driver and truck movements, so their routes must be synchronized in time and space.

While the impact of platooning on fuel economy has been well studied, research on potential labor cost savings is scarce. Our work addresses this research gap and studies the joint truck and driver routing and scheduling problem for Level-4-automated platoons. We model this problem on a time-expanded three-layer network and propose a solution methodology based on nested Benders decomposition. Preliminary results show substantial cost savings and driver count reductions in certain settings and indicate that the possibility of driver exchanges leads to faster deliveries.

4 - Robots at your service: innovative last-mile delivery in omnichannel retail
Manuel Ostermeier, Tobias Huf

The number of home deliveries is ever increasing. This trend is nowadays not restricted to standard shopping but comprises a versatile product spectrum and likewise a variety of delivery modes and channels. Retailers establish omnichannel networks to address these challenges. Goods are not only supplied via central warehouses but frequently delivered direct from stores. This enables a timely delivery and a satisfying shopping experience. Yet this goes hand in hand with complex logistics, and efficient solutions for the last mile of deliveries are needed. To address these challenges, we propose the concept of combining delivery trucks with autonomous robots. The concept uses robots carried by a dedicated truck for last-mile delivery and leverages an infrastructure of robot depots and drop-off locations. Robots are released at the available network locations and travel the last mile to the customers. The deliveries happen within predefined time windows such that customers can retrieve their parcels from the robots at the promised delivery time. We further extend the concept by integrating store locations and corresponding customer requests for direct supply form stores. This results in an innovative logistics concept, where robots are offered as a service for pickup and delivery request in an omnichannel environment. We formulate the resulting problem as a mixed integer program (MIP), and propose a tailored solution approach, the Adaptive Genetic Algorithm (AGA), based on a novel recombination-based search. The AGA addresses the problem-specifics (e.g., the possibility of no visit or multiple visits per location) using specialized recombination operators and an adaptive search strategy to guide the search towards an efficient selection of (truck) stop locations.

■ WB-14

Wednesday, 10:30-12:00 - ESA W(est) 120

Robust Optimization in Transportation

Stream: Mobility and Traffic
Invited session
Chair: *Kianoush Mousavi*

1 - On the flexibility of using marginal distribution choice models in traffic equilibrium
Selin Ahipasaoglu, Ugur Arikan, Karthik Natarajan

Traffic equilibrium models are fundamental to the analysis of transportation systems. The stochastic user equilibrium (SUE) model which relaxes the perfect information assumption of the deterministic user equilibrium is one such model. The aim of this paper is to present the MDM-SUE model, that uses the marginal distribution model (MDM) as the underlying route choice model. In this choice model, the marginal distributions of the path utilities are specified but the joint distribution is not. By focusing on the joint distribution that maximizes expected utility, we show that MDM-SUE exists and is unique under mild assumptions on the marginal distributions. We develop a convex optimization formulation for the MDM-SUE. For specific choices of marginal distributions, the MDM-SUE model recreates the optimization formulation of logit SUE and weibit SUE. Moreover, the model is flexible since it can capture perception variance scaling at the route level and allows for modeling different user preferences by allowing for skewed distributions and heavy tailed distributions. The model can also be generalized to incorporate bounded support distributions and discrete distributions which allows to distinguish between used and unused routes within the SUE framework. We adapt the method of successive averages to develop an efficient approach to compute MDM-SUE traffic flows. In our numerical experiments, we test the ability of MDM-SUE to relax the assumption that the error terms are independently and identically distributed random variables as in the logit models and study the additional modeling flexibility that MDM-SUE provides on small-sized networks as well as on the large network of the city of Winnipeg.

2 - Drone Network Design for Transmission Line Inspection in Electricity Grids
Kianoush Mousavi, Daniel Kuhn

Drones can help to inspect critical infrastructures including electricity transmission lines, railway tracks, roads, bridges or wind turbines. The benefits of using drones are particularly pronounced in mountainous or remote areas that are difficult to access. In case of an unexpected line failure in an electricity grid, for example, drones can quickly inspect the failure location and thereby speed up the provision of corrective measures. In this talk, we develop an optimization model for selecting the locations of drone hubs in an electricity network. The model aims to minimize the costs of opening the hubs and acquiring the drones while ensuring that every possible failure location can be reached within a prescribed time limit. We assume that drones can only fly along transmission lines and take into account that fuel consumption and horizontal speed adapt to the changing slope of the underlying terrain. We further study a variant of the basic model which accounts for the possibility of multiple line failures and thus requires a simultaneous dispatching of several drones. We show that the proposed model can be cast as a mixed-integer linear program and present the results of a case study based on the Swiss electricity transmission network.

3 - Robustness Concepts for Periodic Timetabling
Vera Grafe, Anita Schöbel

An important aspect of optimising public transport is finding a good timetable. On the one hand, short travelling times are important from the passengers' point of view. On the other hand, tight timetables without buffer times are prone to delays, which are inevitable in practice and highly dissatisfactory for the passengers. Hence, a good timetable should also have some degree of delay resistance. Often a periodic timetable is desirable, i.e. a timetable which repeats in a regular pattern (e.g. every hour). However, delays do in general not occur periodically, so many robust timetable models only consider aperiodic timetables. In our work we analyse different robustness concepts, such as strict robustness, light robustness and adjustable robustness, in the context of periodic timetabling, where we allow aperiodic delays. Furthermore, we present a new model using recovery robustness, which is the first one to consider periodic timetables with aperiodic delays. We compare the different models with respect to the real travelling time, analyse the relations between the models in special cases and discuss for which of these concepts considering aperiodic delays is actually equivalent to only considering periodic delays, and for which it does indeed make a difference.

4 - Robust Facility Location in Disaster Preparation for Earthquakes with Aftershocks

Laurent Alfandari, Ivana Ljubic, Minakshi Punam Mandal

In our study, we focus on the preparedness phase of a disaster management system. We consider a two-stage facility location problem for prepositioning relief materials, particularly for earthquakes. In the first stage, the area is affected by the first earthquake. Most earthquakes are followed by several aftershocks, which we consider the second stage of the problem. These aftershocks can either be earthquakes of magnitude comparable to the first earthquake or earthquakes of smaller magnitudes and result in other disasters like tsunamis. This results in deaths, injured, and thousands of displaced people, who have limited to no access to basic human amenities like food, water, medicines, blankets, etc., for several days. The decision-maker wants to set up warehouses or facilities to store such relief materials that can be used to help these people in need and serve the entire demand caused by such emergencies. Demand nodes are assigned to selected warehouses based on transportation cost or distances, taking into account the worst case of aftershocks scenarios for the second stage. The demand at each node is a function of the population and the distance to the epicenter or aftershock. We propose a Gamma-robustness approach for the second stage, with the particularity to lie on binary variables associated to the location of the aftershocks, instead of a box interval as usually done in the literature. We devise a compact formulation, an extended formulation, and several branch-and-cut approaches for the problem. We compare the performance of the various approaches on a dataset based on the recent major earthquake in Turkey, and provide managerial insights for disaster preparedness.

■ WB-15

Wednesday, 10:30-12:00 - R 0077, VMP5

Capacity Planning in Health Care

Stream: Health Care Management
Invited session
Chair: *Emilia Grass*

1 - The Resilient Newsvendor: Hospital Surge Capacity Planning

Emilia Grass, Raik Stolletz

The number and intensity of natural disasters is constantly increasing and have an ever-greater impact. Due to urbanization, Due to urbanization, more and more people are affected by such catastrophic events, requiring hospitalization. It is crucial for a society to ensure that hospitals are resilient in such situations and existing capacities are used in an optimal way. Hospital resilience is defined as the capability to maintain and expand medical capacity and to respond to sudden and significant increases in patient demand. In this context, bed availability is critical to hospital performance and resilience, where surge beds are beds, not operational or staffed, that can be deployed if necessary. Although the most common disasters, such as storms and floods, can be predicted about 72 hours in advance, hospitals are often overwhelmed with the surge in demand. In order to increase surge beds for disaster victims in the short term, either elective appointments are cancelled or patients are discharged too early, which can lead to patient harm. In this study, we define the first resilience metric to measure the service level of hospitals in disaster situations based on cancellations, patient discharges, and rejections. In addition, a newsvendor model is proposed for building hospital resilience by planning their surge bed capacity for short-term predictable disasters.

2 - Algorithmic decision support for operational and strategic advancement of prehospital care

Christoph Strauss

Most strategies to improve prehospital care management focus on efficient resource management of emergency services and neglect long-term implications on the prehospital healthcare system, i.e. emergency departments and public healthcare institutions. We present recent results from simulation projects in Switzerland that demonstrate how simulations (e.g. discrete event simulations) change healthcare planning in the long term by (1) quantifying the effects of various measures and policies, (2) developing a common language (joint development of so-called boundary objects), and (3) contributing to the development of strategies that improve prehospital care at unchanged costs. We use a real-life project with the canton of Zurich to explain our simulations and how strong interactions between emergency medical services, emergency departments, and public healthcare institutions occur. Furthermore, we show in what sense these interactions significantly influence current care planning. In the scientific literature, interactions between important players in prehospital care is only a very marginal topic. However, experts and decision makers from the field widely agree that interactions become essential for high-quality care planning. We therefore propose a methodology that models care planning as an interdisciplinary process using a combination of system dynamics and mathematical optimization. We present initial indications that this methodology enables optimization at strategic, tactical, and operational planning levels, involving emergency medical services, emergency departments, and public healthcare institutions simultaneously.

3 - Interactions between hospital case mix and medical resident planning

Sebastian Kraul

The case mix planning problem deals with selecting the ideal mix and volume of patients in a hospital and is an important tool for strategic and tactical hospital planning. Case mix planning aims to match patients with the appropriate level of care and resources to improve the quality of care, reduce costs, and increase the overall efficiency of hospitals. The choice of the patient mix directly impacts the potential number of medical residents to be trained by a hospital because the patient mix is related to the content relevant to residents' training (specific number of procedures). In order to take a holistic view of the medical resident training in the hospital, it is necessary to consider case mix planning and analyze it from the perspective of medical resident planning. In this research, we will formulate the integrated problem as a mixed integer program and analyze different settings.

4 - Improving Hospital Layout Design with Transformability: A Case Study Using a Meta-Heuristic Algorithm

Shiva Faeghinezhad, Yuhao Gao, Lena Wecken, Kunibert Lennerts, Peter Nyhuis

Transformability is a system property that describes the ability to implement changes quickly and at low cost. This property is becoming increasingly important in hospital design due to the ever-changing nature of the healthcare sector. Hospitals are under constant cost pressure, and the use of transformable layout designs enables them to adapt to changing needs and technological advances without the need for extensive and expensive redesigns. However, current hospital layout design methods often focus solely on optimising traffic flows, such as those of patients, staff or supplies, without considering the notion of transformability. To address this gap, this paper proposes a new layout design approach that integrates transformability into the process. In this paper, transformability is defined as including modularity of spaces, compactness of layout and free expansion areas. To solve the hospital layout design problem, this paper proposes a meta-heuristic algorithm for the quadratic assignment problem based on genetic algorithms. A hypothetical case study is presented to demonstrate the capabilities of the proposed method. The results suggest that the proposed method can produce feasible layout designs that respect transformable building features.

■ WB-16

Wednesday, 10:30-12:00 - R 0079, VMP5

What's New in Solvers

Stream: Software for OR
Invited session
Chair: *Timo Berthold*

1 - HiGHS: Improving the best open-source linear optimization software

Julian Hall

HiGHS is open-source software for large scale linear optimization, and has established itself as offering the best benchmark performance due to its innovative interior point (IPM) solver for LP, and powerful MIP solver. In particular, the IPM solver has been hailed as a game-changer for the field of open-source energy system modelling. However, for some instances, the IPM solver is still prohibitively expensive. This

talk will discuss how performance of the IPM solver can be enhanced, and plans for a new IPM solver for HiGHS. The talk will also summarise other recent enhancements of HiGHS.

2 - Recent Advances in Modeling and Solving Optimization Problems with SAS
Philipp Christophel

In this talk we show various ways to solve optimization problems with SAS, including the OPTMODEL modeling language and Python. We also report on recent advances in the linear and mixed integer solvers.

3 - Gurobi's Ill-Conditioning Explainer
Matthias Miltenberger, Ed Klotz

Ill-conditioning in LP and MIP models remains a challenge for optimization practitioners. While Gurobi uses numerically stable implementations of its algorithms that solve most models without trouble, highly ill-conditioned models can yield inconsistent results or low solution quality that are difficult and time-consuming for the practitioner to resolve. The best solution to those issues is to improve the formulation of the problem instance by going back to the modeling stage. Gurobi's newly developed ill-conditioning explainer can help identify the root causes of numerical troubles and provides helpful information to mitigate them. We present this open-source tool and demonstrate how it can help avoid common sources of ill-conditioning. Our method targets linear optimization problems but can also be applied to mixed-integer models because of their reliance on handling LPs during the solving process.

4 - What's new in FICO Xpress Solver?
Timo Berthold

We present the latest developments of the FICO Xpress Solver, with enhancements to its algorithms for linear, mixed-integer, and nonlinear optimization problems. One of the newest features is Xpress Global, which allows users to solve mixed-integer nonlinear programming problems to proven global optimality.

■ WB-17

Wednesday, 10:30-12:00 - ESA O(st) 121

Discrete Optimization Applications I

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Michael Simonis*

1 - Integrated shelf-life rules for multi-level tablets manufacturing processes
Michael Simonis, Stefan Nickel

This paper discusses the multi-level capacitated lot-sizing problem with linked lot sizes and backorders (MLCLSP-L-B) considering deterministic product shelf-life applied on tablets manufacturing processes. Shelf-life is modelled by integrated shelf-life rules in tablets manufacturing processes. Thus, the MLCLSP-L-B is extended by integrated shelf-life rules (MLCLSP-L-B-SL). An exact mathematical problem formulation is provided. Three established benchmark approaches from literature, namely First In-First Out (FIFO), First-Expire First-Out (FEFO) and isolated shelf-life rules, are used to discuss model outcomes compared to MLCLSP-L-B-SL. Evaluation based on anonymized real-world data of five multi-level tablets manufacturing problem instances. Additionally, proposed solutions are compared in terms of manufacturing costs and shelf-life conflicts. Finally, planning rules and managerial insights are given for tablets manufacturing processes.

2 - Risk-Averse Dynamic Antibiotic Time Machine Problem
Deniz Tuncer, Burak Kocuk

Antibiotic resistance is a global healthcare issue. As a result of repeated and uncontrolled antibiotic applications, the bacteria might mutate and become resistant to the antibiotics that we use. This results in inefficient treatments and sometimes need of developing new drugs for a certain type of bacterium. Given a treatment length and a set of antibiotics, antibiotic time machine problem aims to maximize the probability of reversing the mutations that lead to antibiotic resistance. We are interested in the dynamic version of the problem in which after each antibiotic application, the genome of the bacterium is observed, and the next antibiotic application is made accordingly. This problem can be modeled as a Markov Decision Process, which allows for maximizing the expected probability of reversing the mutations. However, we claim that given the seriousness of the issue, obtaining risk averse solutions would be a reasonable approach. To this aim, we formulate a risk-averse mixed-integer linear programming (MILP) model for this problem with scenarios in which the risk is measured using conditional value-at-risk. Since this is a challenging problem, we propose a risk-averse scenario decomposition algorithm. Our decomposition approach partitions the scenario set into group subproblems and each group subproblem is solved as a risk-averse MILP. This allows us to construct lower and upper bounds for the optimal value of the original problem based on the optimal values and solutions of the group subproblems. We also enhance the standard algorithm with improved cuts by exploiting the special structure of the problem. We conduct computational experiments with real data and obtain promising results.

3 - Joint shelf design and space planning problem with placement options and varying display orientation
Sandra Zajac

In grocery retail, shelf space is a valuable asset in both food and non-food area wherefore it is essential to manage it efficiently. Literature focuses on the space planning in the food segment where products are traditionally placed on shelf boards. In the non-food area, however, some products are placed on shelf boards while others are hung on the perforated back wall of the shelf rack. For practical reasons, the display orientation of the product may change if a product is placed on a shelf board instead of being hung up. In that case, the width and height of a product facing depends on the chosen placement type. In this talk, the joint shelf design and space planning problem with placement options and varying display orientation is introduced. The objective is to maximize the total profit taking space-elastic demand into account. The shelf design is determined by defining the required number and position of shelf boards and hence the space allocated to floor and hanging placements. For each listed product, space and placement type have to be assigned. Lastly, the products have to be positioned both vertically and horizontally on the shelf rack. In our talk, we present a linear mathematical program for this innovative problem. The problem is solved for both random test instances and a realistic case study and some insights are shared.

4 - Hydrogen-powered aviation: An optimization approach deciding on where to incorporate Hydrogen into the air traffic sector
Lisa-Marie Manke, Imke Joormann

The pressure on the air traffic sector to reduce the amount of emitted CO_2 emissions is continuously increasing. Green hydrogen offers an alternative aircraft fuel that is CO_2 neutral. However, the production is very energy-intensive, which could lead to different prices at different production sites due to geological differences regarding possibilities to generate renewable energy. On the other hand, the amount of available hydrogen at airports will differ because of the divergent potential in building necessary infrastructure. Furthermore, the number of available hydrogen-powered aircraft will not be enough to serve all of the European air traffic demand. Hence, there is a need to plan which routes are actually operable on a hydrogen basis.

For this purpose, we set up a MILP deciding how best to use the available hydrogen and hydrogen-powered aircraft for the European aviation sector. This MILP consists of two parts, one handling the flow of passenger demand through the network via a multi-commodity flow problem and one handling the hydrogen refueling, where it is possible that aircraft can be refueled for more than one flight-leg. The solution is a network showing which routes within Europe will be operated by hydrogen-powered aircraft and which ones conventionally.

■ WB-18

Wednesday, 10:30-12:00 - ESA O(st) 122

Facility Layout and Location

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Anja Fischer*

1 - Combining the Single Row Facility Layout Problem and Scheduling Aspects

Anja Fischer

In the standard Single Row Facility Layout Problem (SRFLP) one is given a set of departments, their lengths and pairwise transport weights between the departments. One looks for an arrangement of the departments in one line such that the sum of the weighted distances is minimized. But in practice, especially in job shop production systems, there are several departments which are of the same or similar type and could do the same job steps. For this reason we assume that we are given a set of products which have to be produced. For each of these we are given a task list and information on which of the departments a task could be processed. Then we look on the one hand for an assignment of the single tasks for the products to the departments such that the capacity of the departments is not exceeded and on the other hand for an SRFLP layout such that the sum of the transport lengths of all the products is minimized. We present new models for this new extended problem where one of these is based on the well known betweenness model for the SRFLP. We present some preliminary computational results and give suggestions for future work.

2 - Valid inequalities and preprocessing for the capacitated facility location problem with preference constraints

Sophia Wrede, Christina Büsing, Markus Leitner

In the classical Capacitated Facility Location Problem (CFLP), a set of facilities needs to be chosen in order to cover the demand of customers. Customers are assigned to any open facility such that the capacity constraint of the facility is not exceeded. However, in many applications customers are not willing to travel to any open facility assigned to them but want to select an open facility according to their preferences. The Capacitated Facility Location Problem with Preference Constraints (CFLP-PC) takes this behavior into account by assigning each customer to their most preferred open facility.

Both the CFLP and CFLP-PC are strongly NP-complete. Preference constraints, however, imply certain structures in solutions which do not occur in CFLPs. While these structures have already been studied for Uncapacitated Facility Location Problems with Preference Constraints, their use for the capacitated case is not yet well explored. These implied structures render some previously NP-complete special cases of the CFLP easy to solve; this highlights the potential of these insights for improving the MIP formulation. In this talk, we discuss these structures as well as how to use them in combination with capacities in order to derive new valid inequalities for a classical MIP formulation for the CFLP-PC. Furthermore, we propose problem specific preprocessing procedures, which are also based on the combination of structures induced by preference constraints and capacities. Eventually, we show in a computational study that these approaches have a positive impact on the computational run-time for solving the MIP.

■ WB-19

Wednesday, 10:30-12:00 - ESA O(st) 123

Discrete optimization under uncertainty

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Jan Rolfes*

1 - Online Learning for Distributionally Robust Optimization

Kevin-Martin Aigner, Andreas Bärmann, Kristin Braun, Frauke Liers, Sebastian Pokutta, Oskar Schneider, Kartikey Sharma, Sebastian Tschuppik

Stochastic Optimization (SO) is a classical approach for optimization under uncertainty that typically requires knowledge about the probability distribution of uncertain parameters. As the latter is often unknown, Distributionally Robust Optimization (DRO) provides a strong alternative that determines the best guaranteed solution over a set of distributions (ambiguity set). In this work, we present an approach for DRO that uses online learning and scenario observations as a data stream to learn more about the unknown probability. Our robust solutions adapt over time and reduce the cost of protection with shrinking ambiguity. The robust solutions converge to the SO solution for various kinds of ambiguity sets. Our algorithm achieves the optimization and learning goals without solving the DRO problem exactly at any step. We also provide a sublinear regret bound for the quality of the online strategy. Furthermore, we illustrate the effectiveness of our procedure by numerical experiments on mixed-integer optimization instances from popular benchmark libraries and give practical examples stemming from telecommunications and routing. Our algorithm is able to solve the DRO over time problem significantly faster than standard reformulations.

2 - Approximation Guarantees for Min-max-min Robust Optimization and K-Adaptability under Objective Uncertainty

Jannis Kurtz

In this work we investigate the k-adaptability approach for linear problems with uncertain cost coefficients. This approach can be used to find approximate solutions for two-stage robust optimization problems with integer second-stage variables. The idea is to calculate a set of k second-stage solutions already in the first stage, and choose the best one for each scenario in the uncertainty set. While solution algorithms for the k-adaptability approach were intensively studied in the last years, there is not much known about the approximation guarantee the k-adaptability approach provides regarding the corresponding two-stage robust problem. In this work we will derive approximation results for the min-max-min robust optimization problem and show that they can be extended to the k-adaptability problem. We can show that k, the number of solutions required to achieve a certain approximation guarantee, can be significantly smaller than the dimension of the problem. Furthermore, our approximation algorithm can be incorporated into a branch & bound framework to solve the min-max-min robust problem efficiently for larger values of k.

3 - Alternating mixed-integer programming and neural network training for approximating stochastic two-stage problems

Jan Rolfes, Shudian Zhao

The presented work addresses two-stage stochastic programs (2SPs), a broadly applicable model to capture optimization problems subject to uncertain parameters with adjustable decision variables. In case the adjustable or second-stage variables contain discrete decisions, the corresponding 2SPs are known to be $mathrmNP$-complete. The standard approach of forming a single-stage deterministic equivalent problem can be computationally challenging even for small instances, as the number of variables and constraints scales with the number of scenarios. To avoid forming a potentially huge MILP problem, we build upon an approach of approximating the expected value of the second-stage problem by a neural network (NN) and encoding the resulting NN into the first-stage problem. The proposed algorithm alternates between optimizing the first-stage variables and retraining the NN. We demonstrate the value of our approach with the example of computing operating points in power systems by showing that the alternating approach provides improved first-stage decisions and a tighter approximation between the expected objective and its neural network approximation.

■ WB-20

Wednesday, 10:30-12:00 - ESA W(est) 119

Auctions & Procurement

Stream: Game Theory and Behavioral Management Science
Invited session
Chair: *Nicolas Fugger*

1 - Bidding in Multi-Unit Auctions under Limited Information

Bernhard Kasberger, Kyle Woodward

We study multi-unit auctions in which bidders have limited knowledge of opponent strategies and values. We characterize optimal prior-free bids; these bids minimize the maximal loss in expected utility resulting from uncertainty surrounding opponent behavior. Optimal bids are readily computable despite bidders having multi-dimensional private information, and in certain cases admit closed-form solutions. In the pay-as-bid auction the minimax-loss bid is unique; in the uniform-price

auction the minimax-loss bid is unique if the bidder is allowed to determine the quantities for which they bid, as in many practical applications. We compare minimax-loss bids and auction outcomes across auction formats, and derive testable predictions.

2 - Procurement Design with Loss Averse Bidders
Philippe Gillen

We show that it is beneficial for a buyer to conduct a multi- stage mechanism if bidders are loss averse. In a first step, we derive a revenue equivalence principle. Fixing the multi-stage structure, the revenue is independent of the chosen payment rule. Secondly, we introduce a simple two-stage mechanism which always leads to a decrease in procurement costs compared to any single-stage auction. Finally we derive the optimal efficient two-stage mechanism.

3 - Improving incentive schemes for procurement managers
Sandra Hartmann, Jeff Starck

In multi-period contracts with frequent price renegotiations, it can be challenging to incentivize procurement managers effectively. Traditional incentive schemes may fail to account for the trade-off between initial contract awarding and subsequent renegotiations, leading to suboptimal behavior. For example, tying bonus payments to annual price reductions could encourage procurement managers to accept contracts at inflated prices, making future price reductions easier to achieve but ultimately increasing total costs.

To address this challenge, we propose a theoretical model to evaluate and compare popular incentive schemes based on their impact on procurement manager behavior and outcomes. Furthermore, we aim at designing incentive schemes that promote better procurement outcomes. Our approach seeks to provide practical guidance for companies looking to improve their procurement processes.

4 - Membership rules and stability of partial research coalitions with several heterogeneous firms
Razika Sait

This paper aims to study conditions for stability of partial research coalitions among heterogeneous firms in the framework of a research joint lab with positive externalities. We compare stable coalition structures under the following two rules of coalition formation: the open membership game (Yi and Shin, 1995) and the exclusive membership game (Hart and Kurz, 1983). We show that the open membership rule supports only the grand coalition as an equilibrium. In contrast, the exclusive membership rule maintains the grand coalition as an equilibrium only for small values of spillovers, but for intermediate values of spillovers, the exclusive rule supports multiple asymmetric partial coalitions as an equilibrium and leads to higher social welfare than the open membership rule does.

■ WB-21

Wednesday, 10:30-12:00 - ESA W(est) 122

Re-Enforecement Learning, Neural Networks, Transparancy

Stream: Analytics, Forecasting and A.I.
Invited session

Chair: *Hans Georg Zimmermann*
Chair: *Davina Hartmann*

1 - Search heuristics for learning to route with deep reinforcement learning
Kevin Tierney

Recently, numerous machine learning based methods for combinatorial optimization problems have been proposed that learn to construct solutions in a sequential decision process via reinforcement learning. While these methods can be easily combined with search strategies like sampling and beam search, it is not straightforward to integrate them into a high-level search procedure offering strong search guidance. Recently, several methods have been proposed to search for solutions using deep learned networks, such as efficient active search (EAS) and simulation-guided beam search (SGBS). In this talk, we will discuss the current state-of-the-art for learning to route with deep reinforcement learning and how to find high-quality solutions using search heuristics specific to deep learning procedures. We will survey the performance of deep learned heuristics versus traditional OR heuristics and analyze whether using deep learning for routing is a future method or a passing trend.

2 - Is it worth to go deep? Reinforcement learning vs deep reinforcement learning
Fatemeh Fakhredin, Joern Meissner, Asvin Goel

We revisit solution methods for problems with high dimensional state space, for example, proactive inventory and transshipment models with multiple locations. These problems can be modeled using dynamic programming and can, in principle, be solved to optimality using Bellman's equation. However, the size of the state and decision spaces makes it impossible to find the optimal policy for real-size problem instances. In the past, forward approximate dynamic programming / reinforcement learning algorithms have been suggested to find a near-optimal transshipment policy. We investigate whether or not the use of deep reinforcement learning, e.g. adding an additional neural network layer, improves solution quality for these problems.

3 - Tuning White Box model with Black Box models: Transparency in credit risk modeling
Marvin Zöllner

In the context of credit risk modeling, more sophisticated machine learning models, such as boosted regression trees, often show higher predictive accuracy than linear regression models. Nevertheless, linear regression remains popular in the credit risk industry, mainly because the lack of explainability and interpretability of machine learning models is incompatible with the requirements of financial regulators. In this study, we propose the use of linear regression with automated variable selection optimized using machine learning. Formally, the most influential variables and interactions in the machine learning model, identified using Shapley values, are used as predictors of linear regression. This approach allows us to capture the correct linear and nonlinear effects that can arise in credit data while preserving the intrinsic interpretability of linear regression. Based on Monte Carlo experiment and an empirical analysis using two real-life credit default datasets, we show that linear regression with the optimal variable set can predict credit risk significantly more accurately than regressions that use standard variable selection techniques and is competitively comparable with the best machine learning methods.

4 - Cumulative Quantile Loss for the Multi-Period Newsvendor
Leif Feddersen, Catherine Cleophas

The newsvendor problem seeks the ideal order quantity for a single period, such as a day in the case of newspapers or a season for fashion products. Classical solution approaches compute the optimal service level, or newsvendor quantile, by considering the costs of insufficient (underage) and excessive (overage) inventory and sampling the corresponding order quantity from a known demand distribution. Recent research on the data-driven newsvendor problem treats the demand distribution as uncertain, approximating it through historical data and covariate features for a single period. However, retailers face varying replenishment periods in periodic review order-up-to (T, S) policies for different products based on their perishability, leading to a multi-product, multi-period inventory problem. This contribution introduces a problem-specific cumulative quantile loss function to find data-driven optimal order quantities in such realistic problem settings using recurrent and transformer-based neural network architectures. Thereby, we propose an approach that circumvents the otherwise infeasible problem of aggregating non-normally distributed daily forecasts. To evaluate its performance, we benchmark the resulting inventory decisions against conventional approaches in three real-world retail datasets. We discuss practical implications and explore the potential for extending our method to accommodate data-driven continuous review inventory policies.

■ WB-23

Wednesday, 10:30-12:00 - ESA W(est) 222

Routing Problems

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session

Chair: *Gül Gündüz*

1 - Improving a Constructive Heuristic for the General Routing Problem

Thu Huong Dang, Adam Letchford, Burak Boyaci

The General Routing Problem (GRP) is a fundamental NP-hard vehicle routing problem, first defined by Orloff in 1974. It contains as special cases the Chinese Postman Problem, the Rural Postman Problem, the Graphical Travelling Salesman Problem (TSP) and the Steiner TSP. we considered the GRP, which is particularly suitable for modelling routing problems that involve road networks. We examine in detail a known constructive heuristic for the GRP, due to Christofides and others. We show how to speed it up, in both theory and practice, while obtaining solutions that are at least as good. Some extensive computational results were also presented, on both existing benchmark instances and 48 new instances created using real road network data. The improvement in solution quality was modest in all cases, but the improvement in running time was dramatic, even amounting to several orders of magnitude in some cases.

2 - Adapting Hybrid Genetic Search for Dynamic Vehicle Routing

Mohammed Ghannam, Ambros Gleixner

The dynamic vehicle routing problem with time windows (DVRPTW) is a generalization of the classical VRPTW, incorporating customer arrivals in batches and demanding real-time routing solutions. This paper focuses on adapting the Hybrid Genetic Search (HGS) algorithm, a successful heuristic for VRPTW, to the dynamic setting.

We discuss the HGS algorithm's relevant components, such as giant-tour representation, cost computation, initial population, crossover, and local search. Our approach modifies these components for DVRPTW to obtain high-quality solutions while limiting future constraints. We devise methods for comparing different-sized solutions, normalizing costs, penalizing missed nodes, and accounting for future epochs, all without requiring prior training as opposed to machine learning approaches.

Computational results are presented against various baseline solutions, including greedy, lazy, random, and advanced heuristics. We analyze the performance of HGS variants with different cost additions and local search strategies. Our adapted HGS algorithm demonstrates significant improvements over the best-performing baseline in solution quality, showcasing its potential in addressing the challenges of DVRPTW.

3 - A GRASP metaheuristic for solving a straddle carrier routing problem at container terminals with quay crane operations

Ahmet Cürebal, Nina Radojicic Matic, Leonard Heilig, Stefan Voss

This paper presents a metaheuristic approach for solving an optimization problem that arises at container terminals where straddle carriers (SCs) transport containers between the stacking areas and the seaside. In such container terminals, operational efficiency depends mainly on routing the SCs. SCs should be deployed according to the order in which containers are unloaded and loaded at the quay cranes, considering the limited capacity of each quay crane's buffer area, where containers are temporarily stored after being handled by a quay crane or a SC. Besides the precedence relations (i.e., container sequences) and buffer capacities, the solution framework considers safety constraints. The efficient routing of SCs directly contributes to minimizing the idle time of quay cranes, thus improving their overall productivity. The turnaround time of vessels is minimized, which is the objective of the problem. A Greedy Randomized Adaptive Search Procedure (GRASP) metaheuristic is proposed to solve the problem. We present a specially designed greedy approach for the construction of initial results. Well-known local search operators for the vehicle routing problem (VRP) are adapted in the local search phase as the routing component of the problem is similar to the VRP with pickup and delivery. The results are compared with those obtained using the mathematical model proposed in the literature, where the authors presented the problem with an integer program and a heuristic solution framework for solving it. Experimental results show that our GRASP obtains good results compared to the results from the literature in terms of the objective function value and computational times. The application of the approach for a major container terminal in the Port of Hamburg is considered.

4 - Assembly line feeding optimization and conflict-free routing for just-in-time manufacturing systems

Gül Gündüz, Kenneth Sörensen, Muhammed Kotan

Conflicts between tow trains can pose a significant threat to the safety and efficiency of just-in-time manufacturing systems, which rely heavily on these tow trains to deliver parts to workstations along assembly lines. In order to address this issue, this study develops an algorithm to optimize such a tow train system and ensure that its operations are conflict-free, i.e., that tow trains do not collide with each other. To achieve this, the complex production layout is divided into "pixels", which allows to evaluate conflicts in a straightforward manner. The A-star algorithm calculates the distance between workstations on this pixel layer, while a Simulated Annealing algorithm identifies the best routes to deliver parts to workstations. Additionally, a novel algorithm detects conflicts and suggests two solutions: either holding a tow train or trying alternative routes.

■ WB-24

Wednesday, 10:30-12:00 - ESA O(st) 120

Flow Shops

Stream: Project Management and Scheduling
Invited session

Chair: *Christin Schumacher*

1 - Customer order scheduling in a permutation flow shop environment

Julius Hoffmann, Janis Sebastian Neufeld, Udo Buscher

The customer order scheduling problem has received much attention in current scheduling research. In contrast to classical scheduling problems, the jobs that have to be scheduled belong to customer orders, which is closer to many real-world production scenarios. An order is only complete when each job of the order has finished. Various problem configurations of the customer order scheduling problem have been studied. We are considering a permutation flow shop environment with m stages and n orders, whereby each order has o jobs. The objective is to minimize the sum of order completion times. To the best of our knowledge, this particular problem configuration has not yet been investigated. In our study, we derive properties of the problem configuration as well as a mathematical programming formulation. Furthermore, we present four heuristics, which are based on the iterated greedy algorithm. In a computational experiment, the algorithms are tested for their practicality and compared with each other. The Gurobi solver solved the formulated MIP optimally for a problem instance with 4 orders, 3 jobs per order and 2 machines in reasonable time. However, for tested problem instances with 5 orders, 4 jobs per order and 3 machines, the Gurobi solver could not find and confirm an optimal solution after eight hours and was outperformed for these problem instances by the four developed algorithms. This shows the relevance of developing heuristics for this configuration of the customer order scheduling problem.

2 - A bi-objective re-entrant flexible flow shop scheduling problem with labour resource constraints

Johanna Mlekusch, Richard Hartl

Due to the increasing complexity of production processes, optimizing workflows is a challenging task for manufacturing companies. In this work, we present a production setting inspired by a real-world company, where the manufacturing process can be modeled as a re-entrant flexible flow shop scheduling problem (RFFS). In addition to the re-entrant characteristic, the problem is characterized by additional resources of workers that need to be assigned to production steps. The considered setting can be characterized as a scheduling problem with dual-resource constraints (DRCRFFS). In the problem at hand, we consider a cross-trained workforce, where workers have heterogenous skill levels, meaning they are qualified for a different amount of stages. We model the DRCRFFS as bi-objective optimization problem. The first objective is to minimize the maximum completion time, as high costs are related to the length of the production period. The second objective is to minimize the production costs, that arise through employee salaries. We consider that every worker is paid for a consecutive period starting from its earliest starting time until its latest completion time on any operation. Further, we assume a worker's salary per time unit is related to their skill level. We first solve the bi-objective DRCRFFS with a preference for the first objective, by applying lexicographic optimization. Further, in order to report the set of non-dominated solutions, we employ the epsilon-constraint technique. Preliminary results indicate that there is much potential for cost reduction by targeting a more compact allocation of operations while maintaining the same throughput.

3 - Comparison of priority rules, machine allocation, and stage allocation strategies for hybrid flow shop instances using combinatorial logic

Dominik Mäckel, Christin Schumacher

The configuration of heuristics strongly impacts the resulting objective function values for given problem instances. Finding the most suitable algorithm components is essential for efficient production scheduling. This paper aims to automatically compare and combine different priority rules, machine allocation, and stage allocation strategies on hybrid flow shop instances with different sets of real-world constraints. To test and tune algorithm configurations and parameters for scheduling problems, an approach with combinatorial logic using the combinatory logic synthesizer is applied. To automatically test scheduling instances, the data representations of those in the literature are reviewed first. A new representation is proposed to harmonize the data sets for a large variety of beta constraints. In the second step, a total of 32 constructive heuristic configurations are constructed automatically using componentization and recombination of four priority rules, four machine assignment strategies, and two stage assignment strategies, along with a general framework of a constructive heuristic. Finally, three sets of test instances with different numbers of jobs by Wittrock (1988), Naderi et al. (2010), and Ruiz et al. (2008) are used to evaluate the resulting constructive heuristics. Over 400,000 evaluations of the makespan objective show clear favorite algorithm combinations for the instances considered.

■ WB-25

Wednesday, 10:30-12:00 - ESA O(st) 222

Optimization Methods in Engineering

Stream: OR in Engineering
Invited session
Chair: *Fabian Meyer*

1 - Inertia-based route planning: Models and solution approaches using multirotor UAVs as an example

Fabian Meyer, Katharina Glock, David Sayah

Motion planning of a robotic system is a complex task, especially when a set of initially unordered target positions must be sequenced. Among others, examples can be found in several surveillance and data collection applications with UAVs. These problems usually consist of a set of waypoints to be visited such that some sort of objective is optimized. From an operational research point of view, these problems are closely related to the traveling salesman problem (TSP) and the orienteering problem (OP). To solve these problems with methods from operations research, UAVs are usually assumed to move with constant velocity and to be able to make sharp turns at any time. However, from a physical point of view, UAVs are inert and have limited kinematic capabilities such as a maximum allowed velocity and acceleration which have to be respected for making turns. Hence, the question arising is as follows: "Is the solution of a classical TSP or OP suitable to solve the problem at hand, or are the assumptions made inappropriate?" In this talk, we give an answer to this question. First, we introduce a mathematical model for inertia-based route planning of physical systems. Next, we give insights into how the edge costs between waypoints are determined such that the kinematic constraints are fulfilled and propose a heuristic solution approach based on an adaptive large neighborhood search (ALNS) to solve the problem. Our computational study results indicate the importance of paying more attention to the actual physical restrictions in solving real-world problems from robotics and manufacturing with methods from operations research.

2 - A Column Generation Approach for Weighted Set Packing Problems with Forbidden Pairs

Johannes Schmidt, Armin Fügenschuh

In the weighted set packing problem (SPP) a finite base set and a weighted family of subsets of this base set are given. One asks for a selection of the subsets with the maximum sum-weight that disjointly covers the base set. This combinatorial optimization problem can be formulated as a binary linear program (BLP). The decision variables determine whether a subset is chosen or not. The columns of the constraint matrix encode the affiliation of an element of the basic set to the respective subset. If the family of subsets is very large (e.g., the power set of the base set), the result is a BLP with an exponential number of columns (w.r.t. the base set), from which usually only a few columns are chosen in a feasible solution. Then column generation methods (CG) offer an algorithmic solution. Here, only certain subsets are generated by solving a sub-problem and then added to the BLP. We consider an extension of the SPP that includes forbidden pairs, i.e., two subsets that cannot be chosen together in a feasible solution. Such conflicts can be formulated by additional linear constraints. Our goal is to integrate such conflict conditions into the column generation procedure. We present a new exact solution algorithm using CG and an additional conflict solution step to solve this problem. At each iteration, the optimal solution found by CG is examined for conflicting columns. Conflicts that arise are handled by a subproblem in order to resolve them locally without changing the objective function value. If this fails, the CG is restarted with additional constraints in the BLP. The applicability of this approach is shown for a team orienteering problem involving multiple UAVs that must maintain safety distances between them.

3 - Integrating Choice-Modelling with Engineering Design Optimization to Maximize Product Acceptance

Marvin Meck, Peter Pelz

Design optimization is a methodology in engineering design that utilizes methods of mathematical optimization to formulate an engineering design task as a mathematical optimization problem in order to identify the (globally-)optimal design. Formulating such optimization problems involves (i) mathematically formulating the quality metrics to be optimized, (ii) expressing the requirement specification as (in-)equality constraints, and lastly (iii) formulating a suitable physical model to describe the set of all physically feasible designs. In practice, specifying the objective, however, may be difficult as there may be multiple conflicting objectives to be negotiated between; for example, the weighing between cost and efficiency of a design. This leads the designer to then consider the problem as a multicriteria optimization problem. In case of custom-made products or systems an optimal trade-off between objectives can be found by directly involving the customer in the decision process. When designing off-the-shelf solutions, customer preferences usually need to be anticipated. In this case, employing optimization techniques is questionable, as it's unclear whether or not the design specification aligns with the customer's preferences. To circumvent this issue, we present an approach to integrate discrete choice modelling with design optimization, thus allowing to directly optimize engineering design for maximum customer acceptance. A case study is used to demonstrate how our new approach can benefit product family optimization. The subject of the case study is the design of micro-cogeneration systems for residential use.

Wednesday, 13:20-14:50

■ WC-02

Wednesday, 13:20-14:50 - ESA B

Decision Analysis in Transport

Stream: Decision Analysis and Support
Invited session
Chair: *Reinhard Madlener*

1 - A prospective road freight fleet replacement model to achieve the Paris Agreement emission goals in Colombia.

Ana Maria Montes, Cristiam Gil, Andres Felipe Rey Ladino, Gordon Wilmsmeier, Emrah Demir, Wessam Abouarghoub, Vasco S. Rodrigues

Colombia is committed to reducing its Greenhouse Gases (GHG) emissions. To achieve the transition towards a low-carbon future, this research proposes a model providing the road freight transport (RFT) industry with alternative pathways based on scenarios tailored to the characteristics of individual companies. By transferring these scenarios from the RFT sector level to the company level, firms can adequately anticipate expected transformation and know when they should renew their fleet and which technologies they should select.

A mixed-integer programming (MIP) model is proposed to support companies in an uncertain future context of fleet management. The model gathers primary data from individual companies on their operations (e.g., routes) and considers several vehicle engine technologies, differentiating traditional fossil fuels (natural gas or diesel) zero-emission technologies (electric or hydrogen), to determine the optimal mix of vehicle technology with the goal to minimize operational and ownership costs and maximize emissions reductions within the Colombian RFT market context. Historical and prospective data on the availability of technologies, vehicle efficiency, and maintenance costs, among others, are employed in the research.

The proposed model enables more informed decision-making processes for private stakeholders; it is derived from a simulation tool adopted by Colombian government, that assesses the effectiveness of a defined pool of strategies that shape policy decisions in the road freight transport sector. The model provides companies insights regarding their optimal fleet configuration, the timing of vehicle replacements, and renewal strategies minimizing Total Cost Ownership (TCO) and achieving the GHG emissions reduction goals.

2 - Simulating the transport demand in cities hosting large-scale events

Tobias Vlcek, Knut Haase, Justus Bonz, Matthes Koch

By understanding the transportation demand and its impact during large-scale events, stakeholders can develop effective transportation plans that promote accessibility, sustainability, and safety. This paper describes a transportation demand simulation focused on metro systems for cities hosting large-scale events. We use a comprehensive and adaptable simulation that considers all participants, including tourists, workers, and residents. Our data-driven simulation utilizes a variety of publicly available data sources to represent the local population, event locations, transport hubs, hotels, and tourist attractions. The movement of individuals is based on the transportation infrastructure, which includes road networks and public transportation. Various factors, such as travel time, current use of the transport infrastructure, and mode choice based on a choice model are included in our simulation. Our results can help identify congestions causing delays and potential overloads in sections of the metro system, at tourist attractions and at event locations. Based on this information, we can develop mitigation strategies and integrate them into the simulation to observe the resulting changes. This allows us to provide valuable insights to policymakers and transportation planners to ensure the safety of all participants.

3 - Crowd Management for the FIFA WC 2022 in Doha: survey-based traffic analysis and forecasting using machine learning methods

Simon Rienks, Fiona Sauerbier, Knut Haase, Martin Spindler

We conducted a survey on the use of different transportation modes during the FIFA Football World Cup in Qatar. The aim of this research is to identify the most important factors influencing decision behaviour and to estimate a utility function that is as close to reality as possible without using subjective but widely used expert knowledge for this purpose. Derived from this, a no show rate will be determined, which will be used for a queuing model in front of the metro stations.

To analyze the dataset, a combination of several methods is used to provide a data-driven approach. The collected dataset already contains many variables and is extended with interaction terms and binary variables (cuts). These cuts are generated by a deep decision tree to approximate non-linear effects. Overall, the utility function of the multinomial logit model to be estimated is high-dimensional and is therefore not estimated with the maximum likelihood method as in classical decision analysis, but with the maximum likelihood method in combination with a Lasso penalty term. This performs data-driven variable selection and estimates a sparse utility function for this high-dimensional problem. For the given dataset, our approach is superior to the classical method and provides higher accuracy in predicting decision behaviour on unknown data.

4 - Ranking and matching an electric car to customer specifications and requirements

Yossi Hadad, Baruch Keren, Dima Alberg

This paper presents an expert system to support sellers and customers in choosing an electric car (EV) that best matches the customers' requirements. The system enables ranking EVs according to the customers' requirements and his/her subjective weight of each criterion. As an example, the paper analyzes a database of 53 different EVs, each with 22 different characteristics, enabling customers to choose the EV that best suits their most important specifications. Based on the customer's requirements and the principle of fuzzy sets, the system assigns a matching value to each criterion. These matching values are the input matrix for a multicriteria ranking method that ranks all the EVs according to their matching scores for a specific customer. The applicability of the proposed method is demonstrated for one customer with specific preferred EV requirements. The uniqueness of our method is the full ranking of EVs according to the requirements and preferences of a specific customer and his/her subjective weight of each criterion. Regular filtering methods screen out EVs and remove an EV even if it slightly exceeds one criterion (for example, a slight deviation in price). Our method may rank such EVs as candidates for purchase while drawing the customer's attention to the number of deviations. That enables the customer to make a better decision.

5 - A tonne-km optimization approach to reduce the number of empty trips of inter-municipal road freight vehicles.

Cristiam Gil, Ana Maria Montes, Andres Felipe Rey Ladino, Gordon Wilmsmeier, Emrah Demir, Wessam Abouarghoub, Vasco S. Rodrigues

In the context of Colombia's commitment to reduce greenhouse gas (GHG) emissions by 51% by 2030, the road freight transport sector represents a significant contributor to these emissions, accounting for 12% of country's total emissions. Reducing the number of empty trips and increasing the capacity utilization in inter-municipal road freight transport (RFT) operations bears the potential to reduce emissions. This research proposes a tonne-kilometer optimization approach to reduce empty trips in inter-municipal RFT, synchronizing trips and maximizing vehicle capacity utilization.

The model acts as a decision support tool to assist transport route planners in making informed decisions on the allocation of freight trips. The model seeks to answer how a centralized information system can be used to make decisions about the availability of vehicles (e.g., capacities, costs, and routes) to transport cargo between cities in Colombia. It delivers valuable information for operators on potential direct savings in operational costs. From a policy-making perspective, this study also provides insights into the potential efficiency gains in productivity by reducing the number of empty trips within the Colombian RFT sector of up to almost 50%. Reducing empty runs increasing asset utilization, delivers operational cost savings and environmental benefits, i.e., GHG emissions.

■ WC-03

Wednesday, 13:20-14:50 - WiWi A, VMP5

Advancements in Location and Inventory Management: Healthcare, Earthquake Preparedness, and Warehouse Operations

Stream: Logistics
Invited session
Chair: *Jan-Niklas Buckow*

1 - The warehouse reshuffling problem with swap moves and time limit

Jan-Niklas Buckow, *Sigrid Knust*

In this talk, we study the warehouse reshuffling problem, where pallets in a storage have to be rearranged in an efficient way. A high-bay warehouse with an automated storage and retrieval system is considered, which is equipped with a twin shuttle stacker crane. This twin shuttle is designed to perform swap moves, where the pallet at a storage location is swapped with the pallet currently loaded on the stacker crane. We study a new problem variant, where the time for reshuffling is limited, and the pallets that are frequently accessed should be stored closely to the input/output-point to keep the warehouse operations efficient. After proposing necessary and sufficient optimality conditions for assignments of pallets to storage locations, we present algorithms to deal with the time limit. Moreover, we prove NP-hardness of two special cases, introduce lower bound procedures, several construction heuristics and a simulated annealing algorithm. Finally, we present computational results on randomly generated instances based on a real-world company setting.

2 - Integration of location and inventory decisions in healthcare supply chains: state of the art and first model

Inez Puttemans, *Kris Braekers*, *An Caris*

Healthcare systems face tight budgets because of government savings. Moreover, hospitals experience rising costs due to the energy crisis and the COVID-19 pandemic. Accordingly, healthcare systems are under pressure. As a result, hospitals continuously seek efficiency improvements while ensuring a high quality of care. About 30% of hospital costs are associated with logistics, making logistics costs the highest after personnel costs. Since hospitals are labor-intensive organizations, improvements are mainly present in hospital logistics. So, optimizing the hospital supply chain is relevant. Integrated decision-making concerning location and inventory has been recognized as an opportunity to improve the hospital supply chain. The critical driver of integrating location and inventory is to achieve inventory pooling benefits. These benefits can be realized by consolidating multiple inventory locations into a single location or a few locations. As a result, improvements such as decreased inventory and operational costs can be achieved, resulting in reduced hospital logistics costs. These improvements may enhance the hospital supply chain to deliver the expected service to patients while dealing with tight budgets. This study makes two main contributions. First, existing literature on integrating location and inventory decisions over the past decade is reviewed, and interesting research opportunities are identified. Second, a first idea for an optimization model to address these opportunities is proposed. In the future, a mathematical formulation will be developed. This model will account for typical healthcare features such as service level constraints, perishability, and emergency deliveries to investigate the integration of location and inventory in a healthcare context.

3 - Quantifying maverick picking in warehouses: a data-driven approach

Aïcha Leroy, *Kris Braekers*, *Benoît Depaire*, *An Caris*

Order picking is recognized as the most expensive warehouse operation, especially for picker-to-parts systems in which order pickers travel through the warehouse to collect products. Typically, order pickers are assumed to follow a pre-determined route. However, in practice, deviations from this route occur. This phenomenon, known as maverick picking, adds uncertainty to the picker routing problem and can lead to longer picking times than expected.

Through qualitative research and simulation experiments on artificial data, existing literature has indicated the detrimental effect maverick picking may have on operational performance. However, a quantitative justification based on real-life data for their conclusions is still lacking. Additionally, recent research has shown that failure to comprehend and incorporate human behavior in order picking models may lead to discontent, chronic stress, employee turnover, and burn-outs for order pickers.

Simultaneously, data on individual order pickers is readily available in many warehouses. Therefore, we propose a data-driven approach to quantify the prevalence of maverick picking and to find patterns that cause them. Firstly, this allows analyzing the real-life impact of maverick picking. Secondly, improved order picking planning models considering these new insights can be proposed.

In this talk, we discuss first insights of applying our approach on a real-life data set. As order picker deviations may manifest in different ways, we identify and quantify both deviations from the planned pick order of items (e.g., skipped locations because of a congested aisle) and deviations from the expected times at which picks are performed (e.g., alternative travel paths).

4 - Location-based analysis between earthquake measurement stations and emergency warehouses: A Case of Türkiye

Ayca Ozceylan, *Mehmet Tanyaş*

Türkiye has experienced many destructive earthquakes in both instrumental and historical periods. Therefore, there is a lot of struggle in all four phases of disaster management, pre-and post-earthquake. Prime Ministry Disaster and Emergency Management Authority (AFAD in Turkish) is the responsible center to mitigate the effects of the earthquakes in Türkiye. Two subjects that are among the duties of AFAD regarding earthquakes are earthquake measurement stations and emergency warehouses. For this purpose, AFAD has opened 26 emergency warehouses throughout Türkiye and placed 950 stations for earthquake measurements. In this study, it will be investigated whether the locations of the emergency warehouses are suitable by checking at the earthquake data recorded by the measurement stations. The earthquake intensity map will be reconstructed for Türkiye according to the locations of the earthquake measurement stations and the earthquake frequency data they recorded. Then, location analyses will be conducted between these measurement data and the locations of 26 emergency warehouses. The minimum number and location of warehouses that will cover all stations at a certain distance will be determined (using set covering) and the locations of the existing warehouses will be questioned. Finally, new warehouse locations will be proposed to cover all stations using maximum coverage location analysis. In this way, it will be ensured that the emergency warehouses are close to or in those regions where earthquakes are observed.

■ WC-04

Wednesday, 13:20-14:50 - WiWi B1, VMP5

Optimization and Planning in Modern Logistics: Insights into Production, Transportation, and Robotized Systems

Stream: Logistics
Invited session
Chair: *Joachim R. Daduna*

1 - Robotized sorting systems: Large-scale scheduling under real-time conditions with limited lookahead

Stefan Schwerdfeger, *Nils Boysen*, *Marlin Wolf Ulmer*

To meet the expectations of demanding customers, there is a trend toward warehouse automation, especially in large e-commerce distribution centers. In this context, this paper considers robotized sorting systems, where autonomous mobile robots are applied to automatically sort products after picking. The robots load individual pieces of stock keeping units (SKUs) at a loading station, drive to the collection points temporarily associated with customer orders, and autonomously release them, e.g., by tilting a tray mounted on top of each robot. In these systems, a huge number of products approach the loading station with an interarrival time of very few seconds. Hence, we have a very challenging real-time environment for the following decisions: First, since pieces of the same SKU are interchangeable among orders with a demand for this specific SKU, we must assign pieces to suitable

orders. Furthermore, each order must be temporarily assigned to a collection point. Finally, we must assign robots to transport jobs. These interdependent decisions become even more involved, since we (typically) do not possess complete knowledge on the arrival sequence but have merely a restricted lookahead of the next approaching products. We show that even in such a fierce environment sophisticated optimization, based on a novel two-step multiple-scenario approach applied under real-time conditions, can be a serviceable tool to significantly improve the sortation throughput. With our approach a limited-lookahead system is shown to almost reach the performance of a (hypothetical) system with complete knowledge on the approaching products.

2 - Rail freight transport in Germany - Quo vadis ?
Joachim R. Daduna

Repeatedly, rail freight transport is put in the foreground as the most important mode for coping with traffic problems in freight transport and also as an essential factor for achieving climate policy goals. In this article we show that this ignores a number of facts that must inevitably lead to a completely different valuation. If we look at data of the modal split in transport volume for 2021, rail freight share is 8.7%, but 84.7% for road freight, whereby only trucks with a payload of 3.5 t or more or 6 t total permissible weight are included. These light vehicles account for more than 85% of the total commercial vehicle stock, so that, even including agricultural transport by tractor-trailer, a real share of rail freight transport of less than 5% must be assumed. Since the freight transport distances are mostly below 150 km, the propagated shift potential is ultimately marginal, also for the use of bi-modal road/rail transport. In addition, there are changes in demand structures, including a drastic decline in bulk transport, increasing backshoring, and dislocated manufacturing structures (additive manufacturing, urban farming, etc.). Moreover there is also better accessibility due to the much greater density of the road network. The always propagated environmental advantages of rail transport will no longer exist in the future, as a completely new situation will arise with the decarbonization of road transport. Rail freight transport will become a niche segment; only container hinterland transport on a European level will still be competitive, assuming that these can be handled via a network of megahubs. Network expansions in the rural area must be seen as a misallocation of public investment, since their traffic impact there must be considered marginal

3 - Planning Scheduled Services in Multimodal Synchronized City Logistics Systems
Julia Lange, Teodor Gabriel Crainic, Timo Gschwind, Walter Rei

Future city logistics systems focus on multi-tier transportation with heterogeneous vehicles, an integration of freight movements into rail-based mobility and minimal spatial requirements. Resource sharing among inbound, outbound and inner-city commodity flows as well as innovative transportation-as-a-service ideas are of significant importance. The presented planning approach is based on two-tier service network design. Transportation services with routes, departure time windows and capacities are given, and waiting time policies at customer and handover locations need to be respected. The goal is to select and schedule a set of services to operate and assign the demands to them so that both operating costs and waiting times are minimized. To avoid requiring additional storage facilities for handovers, exact on-time synchronization of services is considered and constitutes a major challenge. Preliminary results show that the capability of a general mixed-integer programming (MIP) solver is significantly limited when precisely modeling waiting times and respecting satellite capacities. Therefore, a hierarchical MIP-based solution approach using a relaxed model, bound improvements and problem-specific variable fixing is proposed. The computational study supports the usage of these techniques for medium-size instances, and points out promising future research directions.

4 - Branch-Price-and-Cut for the Production Routing Problem
Eric Fauß, Timo Gschwind

The production routing problem (PRP) is an integrated planning problem that combines vehicle routing and lot-sizing decisions. It extends the inventory routing problem (IRP) in which the production quantities are fixed. Given a set of customers and a discrete finite time horizon, the PRP consists of deciding for each period if and how much to produce, the inventories at the depot and the customers, and the vehicle routes. The latter includes the decisions on which customers to serve and the quantities delivered. The objective is to minimize the total costs over the planning horizon consisting of production, inventory and routing cost. One prominent application of the PRP is the vendor managed inventory approach where a vendor produces a product, delivers it to customers, and is also in charge of the inventory management of the customers. In this talk, we propose a path-based formulation for the PRP and a branch-price-and-cut (BPC) algorithm for its solution extending previous work for the IRP from the literature. Valid inequalities are used to strengthen the mathematical formulation and a labeling algorithm for solving the pricing subproblems is employed. Computational tests are conducted on established benchmark instances to evaluate the performance of the proposed BPC algorithm.

■ WC-06

Wednesday, 13:20-14:50 - ESA C

Logistics

Stream: Supply Chain Management
Invited session

Chair: *Anne Lange*

1 - Robust berth allocation planning considering uncertain vessel handling times
Lorenz Kolley, Kathrin Fischer

The aim of berth allocation planning is to derive conflict-free vessel assignments to the quay of a container terminal. The corresponding planning problem is called Berth Allocation Problem (BAP). An important objective of terminal operators in the context of this problem is to provide the best possible service quality to the shipping companies, i.e., especially short waiting times. The berthing schedule resulting from solving a dynamic BAP consists of the berthing times and positions of all vessels that are expected to arrive within a certain timeframe; these vessels are scheduled according to their respective arrival and handling times. However, both these times are uncertain due to different influences, e.g., wind and wave or defect handling equipment. Deviations from the planned handling time lead to delayed vessel departures, which cause waiting time for the succeeding vessels and can ultimately result in conflicts that may impede the schedules' feasibility. Hence, updating or re-planning of berthing schedules can become necessary, but this is costly and may be impossible when a plan is already in execution. Therefore, the aim of this work is to derive robust berthing schedules that enhance the schedules' stability by considering uncertainty already in the planning phase and, thus, are resistant to uncertainties of handling times. Machine learning techniques are applied to approximate vessel handling times based on data from the Automatic Identification System. With a robust optimization approach which is based on Dynamic Time Buffers, uncertainty is proactively considered, resulting in more robust schedules. The results of the new approach are evaluated from an ex post perspective using real ship data from the AIS and actual ship handling times.

2 - Resource sharing in offshore logistics: A case from the Norwegian continental shelf
Andreas Ormevik, Kjetil Fagerholt, Frank Meisel

The production of oil and gas on the Norwegian continental shelf takes place at offshore installations owned and controlled by different operators, located in remote areas exposed to harsh weather conditions. Specialized platform supply vessels (PSVs) are used for servicing the installations with various commodities needed to ensure a stable and continuous production. In the current industry practice, each operator controls its own fleet of PSVs, and each installation is serviced from a dedicated supply base (among several) along the Norwegian coast. In this work, we explore how costs and greenhouse gas emissions from the offshore logistics can be reduced by facilitating for a stronger collaboration and sharing of available resources (vessels and supply bases). We formulate an integer programming model for the supply vessel planning problem with resource sharing, SVPPRS, solved on a weekly basis. Cargo demands are specified for delivery at each installation on particular days. For a given fleet of contracted vessels, we pregenerate a large set of feasible voyages that can be combined to form weekly routes for each vessel. Spot vessels can also be used to meet demands by performing the same voyages at a higher operational cost. Computational experiments are carried out investigating the impact of resource sharing in two dimensions: 1) Operator sharing: allowing installations dedicated to the same supply base (but controlled by different operators) to be serviced by the same vessel, and 2) Base sharing: allowing installations from the same operator to be serviced independent of which supply base it belongs to. Preliminary results based on real data show the potential for significant cost and emission reductions from resource sharing on the Norwegian continental shelf.

3 - Analyzing Uncertainty in Air Cargo Turnaround Times

Anne Lange, Sarah Van der Auweraer

Cargo airlines are continuously challenged to manage their operations efficiently. Turnaround operations contribute to airline success. The reliability of turnaround times is a key driver of on-time performance and delays may propagate and amplify for subsequent flights. In comparison to passenger airlines, all cargo airlines are somewhat more flexible in modifying the schedule of their operations. At the same time, cargo airlines are more tightly coordinated with the entire air cargo transport chain than are passenger airlines, resulting in requirements due to integration and consolidation. In comparison to other modes of cargo transportation, cargo airlines face significant constraints stemming from airport operation procedures, multi-partner processes, high asset costs, and security requirements. Thus, it is our objective to empirically identify features that affect the variance of turnaround times of all cargo airlines. Ultimately, we aim to provide guidance to all cargo airlines to render turnaround processes more predictable. We explore a dataset of three months of flight operations provided by FlightRadar24 and we compare integrator operations with all cargo general cargo airlines based on about 130.000 flights. In analysing the data, we use excess travel time as a proxy for flight delays and suggest approaches to identify aircraft bases from operations data. Our preliminary findings include that general cargo airlines' turnaround operations appear largely unaffected by arrival delay whereas integrator turnaround times do reflect such schedule deviations. In addition, we find that integrator turnaround times are consistently above those of general cargo airlines. We attribute this observation to the higher degree of coordination for integrators.

4 - Agricultural Planning Optimization

Emeline Tenaud

Optimizing the planning of the collection, storage and delivery of agricultural goods is a crucial issue for actors in the agri-food supply chain. In order to limit losses and meet supply demands on time, a business proposes a platform to efficiently plan the transportation of grain between different locations and over multiple time periods. The objective of the problem is to determine how much of each grain should be transported between each location and by which mode of transportation. It is also necessary to manage the storage of grain in the silos: the assignment of the type of grain to each cell in the silo must be decided. These decisions must be made for each period of the problem, a period corresponding to one or several months. The search for solutions to the problem is guided by 3 main criteria: maximizing the collection of produced grains, satisfying the customers' demands and minimizing the transportation costs. The difficulty lies in the continuity between the different periods: indeed, as some types of grain can only be collected at the beginning of the horizon and can only be delivered at the end, it is necessary to be able to ensure the storage of these grains in the meantime. It is therefore necessary to deal with the problem as a whole and not period by period, in order to anticipate demand and manage stocks. This initial problem being too complex to be solved in a direct way, the resolution is carried out by a heuristic approach consisting in splitting this problem into several successive sub-problems, including a flow problem and an allocation problem. Solved with LocalSolver, a mathematical optimization solver based on different operational research techniques, this approach allows to obtain high quality solutions in a reduced time.

■ WC-07

Wednesday, 13:20-14:50 - ESA J

Applications of Multi-Criteria Decision Analysis

Stream: Decision Analysis and Support
Invited session

Chair: *Sebastian Schär*
Chair: *Jutta Geldermann*

1 - Resolving ambiguous preference information in group decision-making: A novel optimization model for consensual decision-making

Sebastian Schär, He Huang, Erik Pohl, Cathy Macharis, Jutta Geldermann

Within many multi-attribute decision-making (MADM) methods, inter-criterial preferences of the decision-makers (DMs) are expressed in the form of criteria weights. Due to its convenience and simplicity, the revised method of Simos is widely applied to elicit criteria weights interactively with the DMs. Especially in group decision-making situations it provides procedural ease and offers a means to engage the dialogue with and in between DMs.Every DM orders a set of cards, where each card represents a criterion, according to the criteria's relative importance. This information is then used to calculate criteria weights to be used as input for an MADM method. However, this can lead to uncertainty in the form of ambiguous preference mappings and thus criteria weight vectors. Therefore, the robust extension of Simos' method determines all possible weight vectors from an ordered set of criteria cards via linear programming. The set of feasible solutions forms a hyper-polyhedron and the dimensionality of the convex feasible region is based on the number of criteria. Although the concerns about robustness are expressed in the scientific literature on Simos' method, there is currently no methodological approach to process this information for consensus reaching in decision problems with multiple DMs. We present an optimization model that determines a consensual alternative by utilizing the ambiguity of the Simos methods' ordinal elicitation procedure. The model is based on the preference ranking organization method for enrichment evaluation (PROMETHEE) and demonstrated at hand of a case study for the assessment of seawater desalination plant concepts in Jordan.

2 - Multicriteria seminar assignments in a university considering preference quotas

Andreas Dellnitz, Damian Pozo, Andreas Kleine

There is a long tradition of assigning students to courses taking into account various objective functions, e.g., maximizing lecturer and student preferences and/or balanced workload within departments, as well as constraints, e.g., such as capacity, minimum workload, and/or degree progress. Theoretical approaches here often provide efficient algorithms that can be useful in academic decision making. In this talk, we discuss the main findings on seminar assignment problems at the FernUniversität in Hagen, Germany, considering lower bounds related to ratios. The incorporation of such bounds is important when, for example, chairs try to meet preference quotas with respect to certain categories of students. Incorporating such bounds, however, undermines the total unimodularity of the multicriteria seminar assignment problem. Nevertheless, can the problem still be solved efficiently? A first step towards answering this question is the basis for this talk.

3 - Multi-Criteria Decision Aiding for Built Heritage Value Evaluation: Model and Application in Quebec City, Canada

Irene Abi-Zeid, Jerome Cerutti

Founded in 1608 and once the capital of France's vast empire in the New World, Quebec City (Canada), a UNESCO world heritage city, is one of the oldest in North America. It prides itself on its long history and takes the preservation of its built heritage seriously, not only for the older buildings, but also for the more modern ones that are significant from an architectural perspective. Like many cities, Quebec City is faced with various economic pressures to allow new profitable real estate investments, sometimes at the expense of buildings with potentially a high heritage value. In order to avoid such undesirable situations, the City recently identified a need for a structured and transparent process to assess the heritage value of a building. This identified need led to our decision aiding project where we conducted a socio-technical intervention to develop a multi-criteria evaluation model, based on the method MACBETH, to validate it and implement it in a simple decision support tool. The requirement was that the developed artefacts must be explicit and transparent enough to be applied with minimum interpretation by various qualified actors. The aim of this talk is to present our action research project and its results, obtained through a co-constructive approach with stakeholders from within and outside the City's management team. We describe the process used to construct the criteria and the weights of an additive value function, subsequently used to classify buildings in one of five categories according to their heritage value. The approach and model developed are, to our knowledge, a first in heritage evaluation and can be extended and applied to different cities, with the potential of rendering heritage evaluation more explicit, rigorous, and transparent.

4 - Value-oriented decision making: Weighting of personal values in career decisions

Mendy Tönsfeuerborn

Personal values are an overarching concept shaping people's motives and guiding their decisions and actions. Therefore, important life choices with far-reaching consequences should be considered and made in accordance with ones personal values. In this study, we examine to which extent the most highly prioritized personal values are reflected by the objectives used in the decision-making process and their weights. Determining the amount of objective weights related to the most prioritized personal values with data from real decision-making situations enables us to evaluate whether the resulting decisions of our subjects are actually in line with the personal values. We analyze data from german students with the help of the Entscheidungsnavi, a free-to-use decision support system that guides a decision process based on the Value-Focused Thinking approach by Keeney. As part of the lecture 'decision theory ', the students were asked to systematically work out a complex decision that was important to them. The Entscheidungsnavi guided the students step by step through the process, starting with a reflection of their personal values. We compare two different settings: In the first setting, the five most prioritized values are automatically considered by the tool when defining the objectives. In the second setting, the decision maker has to define the objectives without this help. Our findings suggest that more than 50% of the objective weighting is based on fundamental objectives attributable to the five most prioritized values. Moreover, the proportion of the objective weighting based on the five most prioritized values is larger in the first setting than in the second one.

■ WC-08

Wednesday, 13:20-14:50 - ESA M

Multilevel Optimization

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Lennart Kauther*

1 - Interdiction Models for Robust Combinatorial Optimization

Mohammad Khosravi, Marc Goerigk

Uncertainty can affect a problem in many forms, be it as imprecise data or because the future is impossible to know. To capture what scenarios can possibly occur, robust optimization approaches require uncertainty sets as a main ingredient. In this study we consider a new type of uncertainty set, applicable to objectives or constraints that involve the L1 norm of the solution, for example to problems where the task is to maximize the size of a set or where this cardinality is not allowed to fall below a certain threshold. The uncertainty set that affects these cardinality terms is defined by a knapsack constraint. We refer to this setting as robust optimization with bounded interdiction. We consider both real-world applications and the theoretical complexity of this model. We introduce different models and solution algorithms using various techniques, including dynamic programming.

2 - General Polyhedral Approximation of Two-Stage Robust Linear Programming

Tim Niemann, Lukas Grunau, Sebastian Stiller

We consider two-stage robust linear programs with a budget of uncertainty for the righthand side. In this scenario set, which is frequently used in robust optimization, the uncertain righthand side for each row lies in an interval and the relative increases summed over all rows are less than a budget. It is known that affine linear policies are best suited for this problem in terms of approximation factor, but their running times are often impractical. This work contributes to a method which is designed to find good approximations with more practical running times.

We develop a General Polyhedral Approximation (GPA) method, in which the uncertainty set is substituted by a finite set of polytopes derived from the vertex set of an arbitrary polytope that dominates the uncertainty set. The method combines the solutions for the individual polytopes and thereby achieves an approximation factor that significantly improves on the literature. Moreover, the method allows for even stronger results on specific problems as we exemplify for the Transportation Location Problem.

Previous piecewise affine methods reach a threshold at the square root of the dimension of the righthand side after which they are not better than a quasi nominal solution, i.e., the power of second stage decisions cannot be used. The GPA method significantly improves the approximation factor before this threshold. After the threshold, as the GPA allows to use scaled budget polytopes, it provides a scheme to trade-off the number of vertices against the approximation factor. This way the GPA breaks the threshold and finds solutions that are better than the quasi nominal solution even for cases with a bigger budget.

3 - The Robust Bilevel Selection Problem

Dorothee Henke

In bilevel optimization problems, two players, the leader and the follower, make their decisions in a hierarchy, and both decisions influence each other. Usually one assumes that both players have full knowledge also of the other player's data. In a more realistic model, uncertainty can be quantified, e.g., using the robust optimization approach: Assume that the leader does not know the follower's objective function precisely, but only knows an uncertainty set of potential follower's objectives, and her aim is to optimize the worst case of the corresponding scenarios. Now the question arises how the computational complexity of bilevel optimization problems changes under the additional complications of this type of uncertainty.

We make a step towards answering this question by examining a simple bilevel problem. In the bilevel selection problem, the leader and the follower each select some items, while a common number of items to select in total is given, and each of the two players maximizes the total value of the selected items, according to different sets of item values. We show that this problem can be solved in polynomial time without uncertainty and then investigate the complexity of its robust version. If the item sets controlled by the leader and by the follower are disjoint, it can still be solved in polynomial time in case of a finite uncertainty set or interval uncertainty. Otherwise, the robust problem version becomes NP-hard, even for a finite uncertainty set.

4 - Knapsack Secretary Through Boosting

Andreas Abels, Kevin Schewior, Moritz Stinzendörfer

We revisit the knapsack-secretary problem (Babaioff et al.; APPROX 2007), a generalization of the classic secretary problem in which items have different sizes and multiple items may be selected if their total size does not exceed the capacity B of a knapsack. Previous works show competitive ratios of 1/(10e) (Babaioff et al.), 1/8.06 (Kesselheim et al.; STOC 2014), and 1/6.65 (Albers, Khan, and Ladewig; APPROX 2019) for the general problem but no definitive answers for the achievable competitive ratio; the best known impossibility remains 1/e as inherited from the classic secretary problem. In an effort to make more qualitative progress, we take an orthogonal approach and give definitive answers for special cases.

Our main result is on the 1-2-knapsack secretary problem, the special case in which B = 2 and all items have sizes 1 or 2, arguably the simplest meaningful generalization of the secretary problem towards the knapsack secretary problem. Our algorithm is simple: It boosts the value of size-1 items by a factor $\alpha > 1$ and then uses the size-oblivious approach by Albers, Khan, and Ladewig. We show by a nontrivial analysis that this algorithm achieves a competitive ratio of 1/e if and only if $1.40 * \alpha \leq e/(e-1) \approx 1.58$.

Towards understanding the general case, we then consider the case when sizes are 1 and B, and B is large. While it remains unclear if 1/e can be achieved in that case, we show that algorithms based only on the relative ranks of the item values can achieve precisely a competitive ratio of 1/(e+1). To show the impossibility, we use a non-trivial generalization of the factor-revealing linear program for the secretary problem (Buchbinder, Jain, and Singh; IPCO 2010).

■ WC-09

Wednesday, 13:20-14:50 - ESA O(st) 221

Conic Optimization and Applications

Stream: Continuous and Global Optimization
Invited session
Chair: *Immanuel Bomze*

1 - Fast Cluster Detection in Networks by First Order Optimization

Immanuel Bomze, Francesco Rinaldi, Damiano Zeffiro

Cluster detection plays a fundamental role in the analysis of data. In this paper, we focus on the use of s-defective clique models for network-based cluster detection and propose a nonlinear optimization approach that efficiently handles those models in practice. In particular, we introduce an equivalent continuous formulation for the problem under analysis, and we analyze some tailored variants of the Frank-Wolfe algorithm that enable us to quickly find maximal s-defective cliques. The good practical behavior of those algorithmic tools, which is closely connected to their support identification properties, makes them very appealing in practical applications. The reported numerical results clearly show the effectiveness of the proposed approach.

2 - Conic relaxations for quadratic optimization problems with exact sparsity term
Bo Peng, Immanuel Bomze

Mixed-binary quadratic optimization problems (MIQPs) plays a significant role in many fields, e.g. interpretable AI, where mixed-binary variables allow us to capture the combinatorial nature of original problems. In this talk, we focus on QPs with an exact sparsity term, the zero-norm, arriving at a significant subclass of MIQP. We present several conic relaxations of this class of problems, and sufficient conditions to ensure exactness. Embedding the relaxation into a Branch-and-Bound (BB) framework, we show that the number of nodes used in the BB is significantly reduced.

3 - Learning for Spatial Branching: An Algorithm Selection Approach
Bissan Ghaddar, Ignacio Gómez-Casares, Julio González-Díaz, Brais González Rodríguez, Beatriz Pateiro-López, Sofía Rodríguez-Ballesteros

The use of machine learning techniques to improve the performance of branch-and-bound optimization algorithms is a very active area in the context of mixed integer linear problems, but little has been done for non-linear optimization. To bridge this gap, we develop a learning framework for spatial branching and show its efficacy in the context of the Reformulation-Linearization Technique for polynomial optimization problems. The proposed learning is performed offline, based on instance-specific features and with no computational overhead when solving new instances. Novel graph-based features are introduced, which turn out to play an important role in the learning. Experiments on different benchmark instances from the literature show that the learning-based branching rule significantly outperforms the standard rules.

4 - Copositive Benders Decomposition approaches to Two-Stage Quadratically Constrained Quadratic Optimization
Markus Gabl

We study Bender's decomposition approaches to nonconvex two-stage stochastic quadratically constrained quadratic problems, based on copositive optimization theory. Since copositive optimization can be understood as a theory of convexifying nonconvex problems, Bender's approaches are a natural way to take advantage of special structure of the often unpractical copositive reformulations. However, there is more than one natural way to do this in the two stage QCQP setting, which leads to different top and lower level problems that come with distinct advantages and disadvantages. In our research we seek to investigate these approaches using analytic methods from copositive optimization theory as well as numerical experiments.

■ WC-11

Wednesday, 13:20-14:50 - ESA H

Agent-based Modeling for Energy Economics and Energy Policy II

Stream: Energy and Environment
Invited session
Chair: *Florian Zimmermann*

1 - Modelling Actor Behaviour in Innovation Networks
Davy van Doren, Markus Voge, Bert Droste-Franke

A significant challenge of the energy transition is the governance of social processes influencing the development and implementation of energy technologies. Classical energy system models have shown limitations to address the complex interplay between different actors operating in technological innovation systems. In the project MANIFOLD (Modelling Actor Behaviour in Innovation Networks), an agent-based model is developed that integrates social-based cause-effect relationships within established energy system models and simulates different options for steering innovation processes. An important aspect addressed by the model regards how the diffusion of technology is influenced by the expertise and existing behavioural patterns of installers, as well as how systemic conditions can influence evolving technology portfolios. Installer behaviour is represented by activities associated to both the installation of products and to the initiation of collaboration structures with fellow installers or technology producers. Another key aspect addressed in the model regards how cost improvements for technology production can be achieved through understanding and managing learning curves. With a focus on sustainable heating technologies, a three-factor learning curve was developed that is determined by production knowledge from research and development, obtained insights through learning-by-doing, and effects resulting from economies of scale. Preliminary results indicate towards the effect that different policy measures can have on energy technology demand management, as well as how framework conditions in relation to educational and operational conditions for both technology producers and installers can be optimised.

2 - The Role of Monetary Evaluation and Social Pressure in the Adoption of Residential Rooftop Photovoltaic Systems
Simon Johanning, Daniel Abitz, Fabian Scheller, Thomas Bruckner

In 2020, private households represented 27.4% of the total final energy consumption in the EU, making them an important factor in climate change mitigation. While institutional change largely depends on (rational) arguments, the behavior of private consumers is a complex amalgamation of opinion dynamics, societal and peer pressure, perceptions, preferences, advertisement and numerous cognitive factors. Understanding the behavior and decisions of consumers is not only important for successful product launch planning, but also for designing policy instrument. Agent-based modelling of innovation diffusion has shown to inform strategies to address these questions.

For this, we developed the agent-based innovation diffusion framework IRPact, aimed at easy and flexible development of models on the diffusion of sustainable products. As an example, we implemented a granular rooftop PV (photovoltaic) diffusion model, PVact, in order to investigate the diffusion of PV systems in private households.

While consumers' behavior depends on a large range of factors, monetary and normative influence are commonly seen to be crucial. In previous research, we have looked at these factors in isolation; however, their interaction is thought to give rise to important dynamics within the system.

In this presentation we will show and discuss the effects that the combination and interaction of monetary evaluation and normative pressure have on the adoption patterns within (an abstracted version of) a real municipal context. Through comparing different levels of model detail, parameter weights and external scenario assumptions, we evaluate overall model behavior and the dynamics of various household segments in order to assess the influence of system elements within the simulation.

3 - Green VRP : The Hybrid Vehicle Routing Problem with Time Window (HVRP-TW)
Amira Belhadj Ammar, Taicir Loukil

For a long time, reducing the overall cost of transportation was a big issue for businesses that improved both performance and profit. As a result, one of the most researched combinatorial optimization issues is the vehicle routing problem. A considerable technological change to human existence, particularly in the area of transportation, offers several benefits in terms of time, safety, and comfort the environment suffers greatly. Therefore, some governments require logistic corporations to incorporate new environmental limitations and objectives for vehicle routing difficulties in order to acquire both commercial and environmentally beneficial solutions, which raised the Green VRP concept. Erdogan & Miller-Hooks (2012) considered the Green VRP as a progression of the conventional VRP. The Hybrid VRP, in which Mancini (2017) described it as a new variation of the traditional VRP, adheres to the same goals as the green vehicle routing problem. Because hybrid vehicles utilize hybrid energy sources, they can get around the issue of a lack of charging stations for electrical vehicles.

Mancini's analysis did not include the time window constraints. This constraint was therefore intended to be included in the mathematical formulation. Thus, in this study we consider the hybrid vehicle routing problem with time window (HVRP-TW) that is a variant or an extension the Vehicle Routing Problem with time window, one of the core problems in combinatorial optimization. Our work will be divided into two main sections, on the first hand we will propose a model proposed with adding the time window constraint and develop a heuristic that solve large-scale instances of HVRP-TW. Finally, we will test the effectiveness of the heuristic.

4 - Modelling the optimization of the regulator settings of a hydro generator fleet as a knapsack problem
Raik Becker, Elias Douglies, Alessandro Filippa, Joakim Allenmark

Transmission System Operators (TSOs) are responsible for balancing the transmission grid by keeping the grid frequency stable at all times. To do so, TSOs buy so-called ancillary services from power market participants. Hydro power is a very flexible power source that can offer such flexibility. Once hydro power producers have sold their flexible capacity on ancillary services markets, they need to decide to which generators this capacity will be allocated. For each generator a regulator setting can be defined. This setting defines how sensitive the regulator reacts to changes in the grid frequency and adjusts the power output. For older regulators (t-reg), four discrete steps can be chosen. For newer models (h-reg), continuous sensitivities can be defined, which makes the optimal choice difficult for a dispatcher. If costs for reserving flexible capacity are defined per generator, the problem can be formulated as a knapsack problem in which the costs are weights and the reserved capacities are values. By discretizing the continuous domain of h-reg regulators, it is possible to reduce the complexity and to use the same constraints for all regulator types. To reduce the increased wear and tear when choosing a high sensitivity and to increase the robustness of the system, it is necessary to spread out the provision of ancillary services to many generators instead of using the full range of the cheapest generator(s). This can be implemented by using multi-objective optimization or by introducing piecewise linear costs. The work at hand compares these options in terms of complexity. Moreover, all other modelling choices are discussed and compared in terms of computational speed when applying the optimization to Vattenfall's hydro power fleet and solving it with Gurobi.

■ WC-12

Wednesday, 13:20-14:50 - ESA K

Model coupling and aggregation for ESM

Stream: Energy and Environment
Invited session
Chair: *Rasmus Bramstoft*

1 - Comparing Methods for Soft-Coupling Energy System Models
Mathias Berg Rosendal

Climate change demands rapid decarbonization of our energy system. However, no clear, optimal transition pathway for achieving net-zero emissions exists. Decision-makers, therefore, rely on energy system modelling. These models must consider many technologies and sectors to account for the increasing penetration of renewable energy and potential system efficiency improvements through sector coupling. To perform holistic analyses, models with different scopes can be soft coupled. However, studies applying soft coupling often do not thoroughly analyse or document the methodology. This paper outlines three categories of bi-directional, soft-linked frameworks used in energy system analyses. Furthermore, a modelling framework that soft-couples two open-source models, Balmorel and Antares, will be developed to test soft-linking methodologies from each category. The aim is to compare convergence times and the pros and cons of each technique. This framework combines the large cross-sectoral scope of Balmorel with the stochastic abilities of Antares, which, in turn, may help decrease uncertainties on renewable energy production or electricity demands and provide valuable insights for policy recommendations and investment decisions on infrastructure. These analyses are expected to improve decision-making in future complex, sector-coupled energy systems with high security of supply.

2 - Time series aggregation for the investigation of sector coupling under consideration of seasonal storages
Alexander Plarre, Christian Perau, Wolf Fichtner

The modelling of large sector-coupled energy systems that consider seasonal storages is becoming increasingly complex. This is mainly but not only due to increasing shares of renewable energies in the electricity mix, the accompanying stronger increase in the volatility of electricity generation and the interdependencies with gas grids. This complexity is reflected in the high number of decision variables of the models, which are necessary for the modelling of longer time periods and high temporal and spatial resolution. In this paper, a complexity reduction methodology is presented to counteract this problem. In a first step, the residual loads of all nodes of all time steps of the model are calculated. The K-Means algorithm identifies similar system states of the overall system from the residual loads formed. Subsequently, the original time series are approximated by using time series aggregation methods. The reduction of the decision variables is realized via column additions of previously identified similar system states. The scenario investigated is storyline B of ENSURE 2 for the year 2030. The Belgian electricity and gas transmission networks are represented here in the considered period of one year in hourly temporal and high spatial resolution, other considered countries of the scenario are represented spatially aggregated in one node. The reduction of the decision variables of the model resulting from this methodology should thus lead to shorter solution times of the model. It can be shown that the methodology used can produce small speed-ups in solution time, with a small underestimation of the actual objective function value. Furthermore, it could be shown that the density of the coefficient matrix of the problem under investigation has a significant influen

3 - Estimating the Carbon Emissions Caused by Electric Vehicle Use in Turkey Using Marginal Emission Factors
Murat Kaya, Tugce Yuksel, Mohamed Maarouf

Electric vehicles (EVs) generate zero carbon emissions during their use; however, the generation of the electricity to charge the EVs does so, the extent of which depends on the primary energy resources used in power generation. In this study, we estimate the increase in power sector carbon emissions caused by the introduction of EVs in Turkey. To this end, we first characterize the hourly EV power demand considering EV model characteristics, trip times, and lengths as well as the charging behaviors of EV users. We then characterize the electricity supply in the Turkish power system by determining the marginal power plants and by estimating the Marginal Emission Factor (MEF) for the system. We use real hourly generation data of the country by fuel type, under four different seasons and three time-of-day periods for different years. Finally, we bring the supply and demand analyses together to calculate the carbon emission caused by the introduction of the hypothetical EV fleet and compare these emissions with that of ICE vehicles. Our analysis yields different results than those obtained by models that use Average Emission Factors (AEFs).

4 - Consistent flow scenario generation based on open data for operational analysis of European gas transport networks
Inci Yueksel-Erguen, Thorsten Koch, Janina Zittel

The transition to decarbonization in Europe has presented significant challenges in ensuring a secure energy supply. Natural gas remains a critical component of the energy mix, but recent political events have demonstrated the need for effective decision-making amidst unexpected disruptions. For instance, the political situation in 2022 led to drastic changes in gas routes throughout Europe. Conducting an operational analysis of the pan-European gas transport network is crucial for understanding the underlying physical network restrictions and the resulting unconventional scenarios. Unfortunately, the limited availability of data presents a significant obstacle in this endeavor. To address this issue, we propose a mathematical model-based method that utilizes open data to facilitate operational analysis of the European gas network. Our approach focuses on the analysis of specific partitions of the gas transport network whose network topology data is readily available. For these partitions, using open data, we generate reproducible gas in/out-flow scenarios conforming to the European gas transport constraints. Employing these scenarios, we enable gas network feasibility analysis and network topology data quality assessment. In this presentation, we report our results on the German high-pressure gas transport network. Our proposed method offers a valuable tool for decision-makers during Europe's energy transition, providing a reliable and comprehensive understanding of the gas transport network's behavior.

■ WC-13

Wednesday, 13:20-14:50 - ESA W(est) 121

Sharing and pooling

Stream: Mobility and Traffic
Invited session
Chair: *Rea Röntgen*

1 - Free-floating electric carsharing problem with partial charging

Rea Röntgen

Free-floating carsharing offers its users the convenience of returning a car rented on a short-term basis to any location within a specified service area. The resulting increase in flexibility for carsharing users is countered by an imbalance of vehicles between different locations, e.g., city districts. To compensate for this, the carsharing provider often hires extra staff to relocate the vehicles. Especially for electric cars, which require more time to recharge at fewer stations than conventional cars, the problem of generating a high level of service for carsharing users while increasing the provider's profit becomes more complex. We therefore consider the problem of scheduling the various customer requests and the resulting charging requests on vehicles with the option of partial charging, and refer to this problem as the free-floating electric carsharing problem with charging and relocation (FFECPR). We formulate it as a MIP model and propose different solution approaches as well.

2 - Dynamic Offer Composition for On-Demand Ride-Sharing Systems

Jarmo Haferkamp

Ride-Sharing systems like MOIA provide shared mobility in urban areas on demand. In such systems, travelers request transportation via a mobile application, specifying their origin and destination. The provider in turn determines efficient routing alternatives to offer pickup times from which the traveler either accepts one or cancels the request. Regarding the acceptance decision of travelers, it is rather not important that the pickup is as soon as possible, but that an offered pickup time corresponds to the individual schedule. For example, travelers who are caught in the rain may want to be picked up immediately, while others need time to get ready, say goodbye, or arrive at the pickup location. The objective of the ride-sharing system is to make an acceptable offer to all requesting travelers, i.e., to minimize the number of cancelled requests. The resulting challenge in designing transportation offers is to meet the uncertain schedules of travelers while maintaining flexibility in routing in favor of likewise uncertain future requests. In this work, we propose a parameterized cost function approximation to address the challenge by balancing empirical acceptance probabilities with an approximated routing effort to identify promising transportation offers. We demonstrate the advantages of this approach in an extensive computational study, including a comparison with benchmarks that exploit different levels of information on travelers' pickup time preferences.

3 - Near Real-Time Routing of Redistributing Vehicles in Bike-Sharing Rebalancing

Felix Gotzler, Gori Camps Tomàs, Damir Safin, Hajime Sekiya, Manuel Wackerle Garcia, Rainer Callies

To make micromobility a success, overhead costs and environmental impact must be lowered significantly. In bike-sharing, this requires the efficient realization and optimization of the vehicle-based rebalancing strategy. For practical applicability, the total problem for a large city has to be solved within one minute on a standard PC. To achieve that goal, a carefully chosen metaheuristic together with an efficient numerical implementation has been developed. Initial solutions, produced by a greedy method, are improved by an advanced Variable Neighborhood Search (VNS) algorithm together with a Large Neighborhood Search (LNS) metaheuristic. VNS is responsible for the local search in the solution space. Different neighborhood operators and operator change strategies have been defined and experimentally compared on real and large data sets for cities like Munich and New York. VNS is robust to bad initializations, but only a relatively localized search strategy - so it is augmented by LNS which better explores the solution space. It is efficient only for small graphs; this can be partly overcome by using stacked model sets and exploiting the inherent parallelism of LNS. Loading instructions are derived for every set of intermediate candidate routes and are used as feasibility checks. They are obtained using exact maximum flow computations on auxiliary graphs. The approach used here is benchmarked against (exact) Branch and Cut methods and provides near-optimal solutions while vastly outperforming the exact method in terms of computational time. The new algorithm has polynomial runtime complexity. Even for very large cities excellent scaling and stability properties are shown.

4 - A Stakeholder-Based View of Business Cases for Integrated Urban Transport

Lena Hörsting, Catherine Cleophas

Integrating urban parcel transport into a public passenger transport system is a promising concept to reduce traffic congestion and use resources more efficiently. However, the last decade saw several promising pilot projects failing due to the lack of long-term support and profitability. Existing reviews show that financial viability is an important aspect for the long-term success of such projects. Integrated transport relies on a range of stakeholders, which differ in their incentives and want to profit from the system. For example, partially financing the public transit system with the revenue gained from parcel transportation may contribute to the success of a shared transport system from the point of view of public transit providers.

In this talk, we first describe the views of relevant stakeholders based on a review of the literature and case studies. Further, we propose performance indicators to evaluate a shared passenger and freight system from the perspective of the individual stakeholders. Secondly, we conceptualize an agent-based simulation model to evaluate business cases for a shared passenger and freight network.

■ WC-14

Wednesday, 13:20-14:50 - ESA W(est) 120

Mobility on demand

Stream: Mobility and Traffic
Invited session
Chair: *Arne Schulz*

1 - A shift scheduling model for a ridepooling service

Arne Schulz, Malte Fliedner

Mobility services often suffer from significantly fluctuating demand such that the demand can increase or decrease strongly within small time windows of for example 15 minutes. The mobility provider needs to address these demand fluctuations by providing a suitable supply without exceeding or undercut the demand too much at any time. However, personal shift schedules underly several judicial restrictions and preferences by the drivers. In this talk, we discuss the aforementioned problem and search for appropriate solutions for the trade-off between a sufficient supply and the drivers' interests in shift scheduling. Thereby, we evaluate the effect of flexible starting times of the shifts of a single driver over the different days of a week. Moreover, we evaluate the effect of working-time accounts. We present a mixed-integer program to determine the drivers' shifts on a monthly base including flexible starting times and working-time accounts and evaluate it for the example of a ridepooling service.

2 - A new event-location-based model for the dial-a-ride problem

Daniela Gaul, Kathrin Klamroth, Christian Pfeiffer, Arne Schulz, Michael Stiglmayr

In the dial-a-ride problem (DARP) a set of transportation requests consisting of pick-up and delivery locations with associated time windows, load and maximum ride time, has to be served by a fleet of vehicles. We present a tight mixed-integer linear programming (MILP) formulation for the DARP by combining two state-of-the-art models into a novel location-augmented-event-based formulation. The formulation is tight in the sense that, if time windows shrink to a single point in time, the linear programming relaxation yields integer (and hence optimal) solutions. Strong valid inequalities and lower and upper bounding techniques are derived to further improve the formulation. We then demonstrate the theoretical and computational superiority of the new model: First, we prove that the new formulation has a tighter linear programming relaxation than the two-index formulation. Second, extensive numerical experiments on benchmark instances show that computational times are on average reduced by 49.7% compared to state-of-the-art event-based approach.

3 - An Event-Based Formulation for the Integrated Dial-a-Ride Problem

Lorenz Saathoff, Arne Schulz

The Integrated Dial-a-Ride Problem (I-DARP) is a complex transport optimisation problem that involves the efficient scheduling of the vehicle routes for a demand-responsive transport service operating around a particular station in a timetable-based public transport system. Traditionally, the DARP is approached using time-space formulations which represent the customer locations as nodes. However, these formulations often face challenges, e.g., computational efficiency. To address these limitations, an event-based approach is introduced, which represents the I-DARP as a sequence of events. The formulation leverages the flexibility of event-based modelling to capture the specific properties of the I-DARP, including many-to-one routing (and vice versa) and coincident desired arrival/departure times at the public transport stop due to the embedded timetable. Each event node corresponds to a change in the vehicle configuration, such as passengers boarding or alighting. The arcs define allowed event sequences. By modelling these events explicitly, many restrictions regarding vehicle capacity, pairing of requests, and precedence constraints can already be respected in the graph construction phase. The idea of this formulation is to find the optimal sequence of events as a directed cycle in the event graph for each vehicle, which corresponds to a flow problem with additional constraints and binary variables. A solver is used to minimise passenger inconvenience in terms of waiting time. Computational experiments on realistic instances are used to evaluate the performance of the event-based formulation for the I-DARP. Additionally, the scalability of the formulation is analysed and its potential for handling real-time instances is discussed.

4 - Computing Optimal Deployment of Mobility On-Demand Public Transport Using Hierarchical Clustering and Voronoi Cells

Marc Gennat, Maurice Görgen

Improving public transport is central to achieving the goals of Germany's energy transition in the transport sector. Long travel times are one of the main reasons for not using public transport, so the development of new models should be considered. On-demand concepts are not common and not yet widely used.

This paper aims to help assess the potential of such concepts for the first and last mile in public transport. It focuses on the conceptual and algorithmic basis. Using the city of Krefeld as an example, a program is developed with the aim of identifying possible areas for pilot on-demand services. After deriving an origin-destination-time matrix for determining demand and extracting street graphs and cadastral data, Voronoi cells with public transport stops as nodes are formed and hierarchically clustered. In each cell, on-demand mobility is simulated. A cost function is established, which serves as the objective function of an integer linear programming model, thus forming an optimal combination of unclustered and clustered cells.

■ WC-15

Wednesday, 13:20-14:50 - R 0077, VMP5

Integrated Planning in Hospitals

Stream: Health Care Management
Invited session
Chair: *Clemens Thielen*

1 - The Dial-a-Ride Problem in Primary Care with Flexible Scheduling

Felix Rauh, Felix Engelhardt, Christina Büsing, Martin Comis, Emma Ahrens

Health is a major factor for the well-being of a society. The demand for health care increases with an aging population. However, many elderly people have limited mobility and thus problems reaching their general practitioner (GP) to obtain treatment. In this context, providing patient transportation is instrumental for lowering access barriers to primary care. However, the economic sustainability of such transportation systems based on ride sharing strongly depends on how well transportation requests can be bundled.

We consider a dial-a-ride setting where the transportation requests consist of a ride to the GP and back. Patients may be chronic or "walk-in" patients, with the latter requiring transportation on short notice. In the general setting, the GPs fix appointments without consideration of the transportation. We propose a novel extension of the dial-a-ride problem, the dial-a-ride problem with combined requests and flexible scheduling (DARPCF). Flexible scheduling in this context means that for chronic patients only an appointment range is fixed a priori, and the exact time is determined when the vehicle routes are computed.

We introduce two heuristics for the DARPCF that are designed to exploit this increased flexibility: Both approaches initially compute mini-clusters of similar requests. Then, the mini-clusters are linked by (i) solving a traveling salesman problem and creating routes with a splitting procedure or by (ii) using a rolling horizon approach and solving bipartite matching problems for the vehicle assignment.

Our computational study shows that with the flexible scheduling of chronic appointments, the average number of served transportation requests can be increased by 16% compared to a non-flexible setting.

2 - Operating Room meets Intensive Care Unit management: Integrated AI-based planning of elective surgeries.

Christina Bartenschlager

Operating Room and Intensive Care Unit capacities belong to the most scarce and expensive resources in hospitals. It is important to consider both resources not in isolation but in an integrated way, for example, when planning elective surgeries. A considerable number of patients is transferred to the Intensive Care Unit after surgery. If Intensive Care resources for such patients are not scheduled in time, surgeries will be postponed or cancelled. In this work, we propose AI-based decision support tools for the prediction of whether an elective patient is transferred to the Intensive Care Unit after surgery. We use a data set of the University Hospital of Augsburg, Germany, consisting of 26,600 elective surgeries that were conducted between 2017 and 2021. The decision support tools integrate the aspects of flexibility and explainability and are evaluated by means of behavioral approaches and simulation. The work is part of the KISIK-project which is funded by the German Federal Ministry of Education and Research.

3 - An Adaptable Web Application for Physician Rostering in Hospitals

Florian Meier, Jan Boeckmann, Clemens Thielen

Physician rostering is an integral part of personnel planning in hospitals that significantly impacts a hospital's smooth operation and employee satisfaction. Good rosters should satisfy complex constraints, encompassing minimum rest times, workload distribution, and individual preferences of the physicians, while an easy-to-use interface allows for hospital integration.

This talk presents an adaptable physician rostering system and its implementation as a web application. To enable a broad applicability, the system employs a general mixed-integer programming model that can be customized via a user-friendly web interface to generate physician rosters that adhere to a wide range of specific requirements faced at different departments or hospitals. Moreover, the web interface allows the convenient collection of all necessary input data including the physicians' preferences for specific duty assignments throughout the planning period. We discuss the challenges faced in designing adaptable physician rostering models such as the consideration of different types of roster structures and outline the system's application at partner hospitals.

4 - Integrated Planning in Hospitals: A Review

Clemens Thielen, Sebastian Rachuba, Melanie Reuter-Oppermann

Efficient planning of scarce resources in hospitals is a challenging task for which a large variety of Operations Research and Management Science approaches have been developed since the 1950s. While efficient planning of single resources such as operating rooms, beds, or specific types of staff can already lead to enormous efficiency gains, integrated planning of several resources has been shown to hold even greater potential, and a large number of integrated planning approaches have been presented in the literature over the past decades.

This talk presents a detailed literature review that focuses specifically on the Operations Research and Management Science literature related to integrated planning of different resources in hospitals. We collect and analyze the relevant literature with respect to different aspects and provide a high-level taxonomy for classifying different resource-focused integration approaches. Moreover, we point out gaps in the literature and promising directions for future research.

■ WC-16

Wednesday, 13:20-14:50 - R 0079, VMP5

What's New in Modeling Systems

Stream: Software for OR
Invited session
Chair: *Filipe Brandão*

1 - Advances in Model-Based Optimization with AMPL

Filipe Brandão

The ideal of model-based optimization is to describe your problem the way you think about it, and then let the computer do the work of getting a solution. Recent enhancements aim to bring the AMPL modeling language and system closer to this ideal. Using a variety of modeling language extensions, common formulations are described more naturally, with the AMPL translator, the AMPL-solver interface, or the solver itself doing most of the needed transformations. Extensions described in this presentation include quadratic expressions, logical operators and constraints, simple near-linear and nonlinear functions, and combinations of these together with linear terms. All are supported by a new C++ AMPL-solver interface library that can be adapted to handle the multiple detection and transformation strategies required by large-scale solvers.

2 - New modelling and programming features in Xpress Mosel 6.4

Susanne Heipcke, Yves Colombani

More than 20 years after its first commercial release, the Xpress Mosel software keeps innovating by introducing new features into the language whilst maintaining a high degree of compatibility for Mosel code written for or compiled with earlier versions. It thus contributes to providing a stable environment for optimization solutions deployed in production environments. New solving features introduced in the most recent versions of Mosel include support for the new global solver of Xpress, the possibility to solve linear and nonlinear optimization problems with multiple objectives, and the introduction of Irreducible Infeasible Sets (IIS) for nonlinear programming problems. On the programming side, the concept of union types introduced with Mosel 6 has found various applications. Usage examples include the implementation of generic libraries, such as generic handling of JSON-format files or dataframe-style input from CSV-format files or databases. The increased use of Mosel for implementing large-scale projects, that are typically organised into a set of user-written libraries, has triggered a need for version management of user-written Mosel code: new annotation markup is now available to state specific package version compatibility rules and also to indicate depreciation. This new functionality is also propagated to the 'moseldoc' tool. Furthermore, Mosel now also supports a 64-bit integer type.

3 - A tour of the GAMS ecosystem in 2023

Andre Schnabel

The GAMS ecosystem surrounding its modeling language has significantly evolved in recent years. There have been major additions like GAMS MIRO, GAMS Transfer, GAMS Engine, and a vastly more modern integrated development environment with GAMS Studio. MIRO allows users to rapidly obtain an interactive web application frontend for a GAMS model with extensive visualization options for the end-user. Transfer makes working with data seamless and more natural in languages such as Python and Matlab. Engine facilitates running GAMS jobs in a cloud environment and thus making even hard problems tractable. Studio is a powerful IDE for GAMS with tight integrations to MIRO and Engine. This talk will give a tour through these new tools and show small examples of their application.

Furthermore, the talk will present the Connect framework. Connect is inspired by the ETL (extract, transform, load) paradigm for integrating data from various sources via agents. With Connect, the user can read data in many different representations into the Connect database. The data is then potentially transformed before being exported into a file format of choice. This approach is general and will simplify migrating data between different formats with optional processing as part of an optimization pipeline built around a GAMS model. We take a short look at how the modern GAMS ecosystem can be used to create a small web application to determine the shortest hiking tour that collects all hiking awards in the Harz mountains in central Germany.

4 - Getting the Best of Both Worlds - Ways to Combine Python's Flexibility with a Domain Specific Modeling Language in Applied Operations Research

Justine Broihan

Applied mathematical optimization involves solving complex real-world problems and it is not always only the model itself that has to be taken care of. Applied Operations Research also requires careful handling and visualization of data in both the development and the production stage. However, data manipulation, preprocessing, and postprocessing can be time-consuming and tedious, especially when working with a domain-specific modeling language such as GAMS. In this talk, we aim to explore how the flexibility of Python and its vast array of available packages can be combined with the efficiency of a domain-specific programming language like GAMS. We will demonstrate this integration using a real-world example and present results on performance.

■ WC-17

Wednesday, 13:20-14:50 - ESA O(st) 121

Discrete Optimization Solution Algorithms I

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Katrin Halbig*

1 - A heuristic approach for solving supply chain management problems with unbounded semi-continuous variables

Katrin Halbig, Dieter Weninger, Ambros Gleixner, Alexander Hoen

Supply chain management problems can contain semi-continuous variables to model operations such as production or transportation. For example, switching off a machine fixes the production quantity to zero, otherwise, the production quantity must satisfy a minimum lot size. If also a maximum lot size is given, this situation can be modeled using binary indicator variables and linear constraints, but in practice an upper bound is not always given. Adding an artificial upper bound (bigM) could cut off optimal solutions or, if the bigM is chosen too large, may lead to numerical instability. In this presentation we discuss how to deal with such unbounded semi-continuous variables and focus on a novel diving heuristic called Indicatordiving. A diving heuristic in general simulates a depth-first search in an auxiliary tree and tries to generate a feasible solution by clever rounding of an infeasible solution given by a relaxation. This technique was implemented in the constraint integer programming solver SCIP and computational results for real world supply chain management problems are presented.

2 - Structure-Based Strengthening of Dual Bounds for Mixed-Integer Programs with Indicator Variables

Björn Morén, Torbjörn Larsson

We consider mixed-integer programs (MIPs) in which the objective function is modelled with indicator variables and there is an underlying geometric structure. Because the modelling of such problems includes big-M values, they have weak LP relaxations and are notoriously difficult. The dual bounds are very weak and improve slowly with a MIP solver, already for small-sized problems with a couple of hundred indicator variables.

Our contribution consists of two parts. First, by utilizing the underlying geometric structure, we propose a decomposition approach, inspired by Lagrangean decomposition, to improve the dual bounds. We partition the indicator variables such that the subproblems can be solved to optimality or near-optimality and provide stronger dual bounds for the full problem. Second, we consider methods for decomposing the problem and suggest an LP-based approach to find effective partitions.

We apply our method to support vector machines with ramp loss, where there is a linearly increasing penalty for misclassified points up to some limit, while the penalty is constant beyond that limit. The purpose is to achieve a classification that is robust to outliers. In this application, the difficulty lies in the objective function, while the constraints lack structure that can be exploited to construct valid inequalities, which is otherwise a common path to improve dual bounds. Our

data set consists of both generated and publicly available instances. We compare dual bounds obtained with our method with the ones obtained from a MIP solver used on the standard MIP formulation and conclude that dual bounds improve much faster.

3 - Dual Conflict Analysis for Mixed-Integer Semidefinite Programs
Marc Pfetsch

Conflict analysis originally tried to exploit the knowledge that certain nodes in a relaxation-based branch-and-bound are infeasible. It has been extended to derive valid constraints also from feasible nodes. This paper adapts this approach to mixed-integer semidefinite programs. Using dual solutions, the primal constraints are aggregated and the resulting inequality can be used at different nodes in the tree to tighten variable bounds. We show that this helps to speed up the solutions times by about 8 %.

4 - Experiments in Cutting Plane Selection for Mixed-Integer Programming
Mark Turner, Timo Berthold, Mathieu Besançon

In this talk, we will cover different aspects of the selection process for cutting planes in the mixed-integer programming solver SCIP. We will explore how the scoring function can be changed to improve performance, and what the most important measures are for determining cutting plane quality. We will then discuss the standard parallelism-based filtering method and introduce a new approach to avoid adding cutting planes that are too similar. We evaluate all the described methods in a comprehensive computational study.

■ WC-18

Wednesday, 13:20-14:50 - ESA O(st) 122

Routing Problems I

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Jeanette Schmidt*

1 - Synchronized Truck and Drone Deliveries
Jeanette Schmidt

In this talk, we consider the vehicle routing problem with time windows and drones (VRPTW-D) as an extension of the classical VRPTW, in which the fleet consists of trucks equipped with one drone each. The idea is that each truck does not only deliver parcels to customers, it also serves as a hub for its drone. On a truck's route, the drone can be released (several times) to perform a single delivery and meet the truck again before it reaches its flight range. In this way, trucks and drones deliver goods to customers as a synchronized working unit. The VRPTW-D consists of finding feasible combined truck and drone routes to serve a given set of customers. A route is feasible if it starts and ends at a given depot, the capacity of trucks and drones is respected, and each customer is served within its time window. The literature distinguishes between two objectives: minimizing the total routing cost and minimizing the summarized duration of all routes. In particular, when the flight range of a drone is limited, an early-as-possible schedule is not necessarily optimal, i.e., waiting before leaving the depot can be beneficial. Therefore, we consider the objective of minimizing the summarized duration between the actual departure and the arrival at the depot for all routes. We propose a branch-and-price algorithm to solve this problem. The column-generation subproblem is modeled as a shortest path problem with resource constraints on an auxiliary network and solved using a dynamic-programming labeling algorithm. Preliminary computational results on benchmark instances are presented.

2 - Bi-directional labeling for the fragility-constrained vehicle routing problem with time windows
Stefan Faldum

The fragility-constraint vehicle routing problem with time windows (F-VRPTW) is a variant of the vehicle routing problem with time windows, where customers are divided into two separate groups with fragile and non-fragile items. These are transported by a fleet of vehicles of identical capacity. The capacity is divided into several identical stacks of a certain width and height. In this case, non-fragile items may not be placed on top of fragile items. Furthermore, no en-route load arrangement is allowed. The problem is solved by a branch-price-and-cut algorithm. Here, the subproblem is a shortest path problem with resource constraints (SPPRC). The standard approach for solving SPPRCs is a dynamic-programming labeling algorithm. A mono-directional labeling algorithm is known and can also be adapted to backward labeling. Note that speeding up the solution time of the subproblem is crucial since solving the subproblem takes 80% of the total solution time in most VRPTW variants. Bi-directional labeling is a helpful tool to reduce the number of labels generated and to speed up the solution time of the subproblem. In this talk, we introduce a dynamic bi-directional labeling algorithm and will focus in particular on the merge procedure of forward and backward labels. Preliminary computational results on benchmark instances from the literature are promising.

3 - On the phase transition of the traveling salesman problem with time windows
Omar Rifki, Thierry Garaix, Sébastien Verel, Christine Solnon

We study the phase transition of the traveling salesman problem with time windows (TSPTW). The decision version of the problem depends on the configuration of the points' time windows: their lengths and positions. We show that the established benchmarks in the literature of the TSPTW, which are mostly randomly generated, lie for a large part in the over-constrained area of the phase transition map. This phenomenon provides a tool for hard benchmark generation. Not accounting for it for randomly generated instances may alter the fair comparison between the solving algorithms designed for the problem.

4 - Farthest Insertion Heuristic for the Traveling Salesperson Problem
Ekin Ergen

The Traveling Salesperson Problem (TSP) is one of the prominent NP-hard problems in combinatorial optimization. Given a complete graph with nonnegative edge weights, the task is to find a minimum-weight Hamiltonian cycle. A special family of approximation algorithms, the insertion heuristics, are widely used in practice, though their performance guarantees in general are not always well-understood. We analyze the behavior of insertion heuristics on (1,2)-TSP, that is, TSP on instances with edge weights 1 or 2. Our analysis on this subproblem yields an approximation ratio which is shown to be tight for three out of four well-known versions of insertion heuristics. For two of these three heuristics, farthest and arbitrary insertions, no tight bounds were previously known for any class of TSP for which the problem remains NP-hard.

■ WC-19

Wednesday, 13:20-14:50 - ESA O(st) 123

Robust Optimization I

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Jenny Segschneider*

1 - Towards Robust Interpretable Optimization
Sebastian Merten, Marc Goerigk, Michael Hartisch

An important factor in the practical implementation of optimization models is the acceptance by the intended users. This is influenced among other factors by the interpretability of the solution process. Decision rules that meet this requirement can be generated using the framework for inherently interpretable optimization models. Furthermore, in practice there is often uncertainty about the parameters of an optimization problem. An established way to deal with this adversity is the concept of robust optimization.

The goal of our work is to combine both concepts to create decision trees for a given optimization problem that are more robust to perturbations and still inherently interpretable. For this purpose, we present a suitable model and solution methods. Furthermore, the applicability of heuristic methods to perform this task is evaluated. Both approaches are compared with the existing framework for inherently interpretable optimization models and tests on real-world data are performed.

2 - Robust Vaccination Schemes with uncertain deliveries

Jenny Segschneider, Arie Koster

Caused by the recent pandemic and the shortage of vaccinations during their roll-out, questions arose regarding the best strategy to achieve immunity throughout the population. For vaccines with two or more doses necessary for full immunization, the problem of setting the time gap between first or second dose for each patient was widely discussed. On the one hand, using a long gap enables reaching partial immunity through one dose only on a larger part of the population earlier in the pandemic. On the other hand, reaching full immunity through two doses earlier will prevent an infection of these patients more efficiently. We call this problem the Two-Dose Scheduling Problem. It can be solved using the theory of b-matchings, where doses are matched into pairs of first and second dose.

Especially during the vaccine roll-out to fight the COVID-19 pandemic, it was shown that deliveries of vaccine are highly uncertain. To include this issue, we propose a model using robust optimization techniques. In practice, appointments for a first dose are often made in advance through booking systems, while the appointments for the second dose are given at the date of the first dose when there is more information about the available number of doses. This leads to a two-stage approach. In the first stage, the number of first doses is fixed for each time step. In the second stage, after realization of the numbers of doses delivered in each time step, the final schedule including second doses is set. This problem is then generalized to a Robust b-matching Problem. We show NP-hardness of a simple variation of both problems and conduct a computational study on the Robust Two-Dose Problem to show the effect of this formulation on expected efficacy and robustness of the solution.

3 - Robust minimum weight perfect b-matching problem under consistent selection constraints

Sabrina Schmitz, Christina Büsing

In this talk, we consider a robust two-stage concept for the minimum weight perfect b-matching problem under discrete demand uncertainty, which we call the robust minimum weight perfect b-matching problem under consistent selection constraints. For this problem, we divide the edges into two types, the so-called fixed and free edges. In a first stage, we irrecoverably decide whether some fixed edges are part of a matching despite uncertain b-values. In a second stage, we decide whether some free edges complete a matching after the b-values are realized. The objective is to find a robust solution that minimizes the worst-case weight over a finite set of b-values. We consider the complexity of the problem on different graph classes such as bipartite, series-parallel, pearl, and cactus graphs. We prove that the problem is NP-complete for bipartite, series-parallel, and cactus graphs. However, we show that the problem is solvable in polynomial time on pearl graphs and for a special case on cactus graphs.

4 - A Branch and Bound Algorithm for Robust Binary Optimization with Budget Uncertainty

Timo Gersing, Christina Büsing, Arie Koster

Robust optimization with budget uncertainty, as proposed by Bertsimas and Sim in the early 2000s, is one of the most popular approaches for integrating uncertainty in optimization problems. The existence of a compact reformulation for MILPs and positive complexity results give the impression that these problems are relatively easy to solve. However, the practical performance of the reformulation is actually quite poor due to its weak linear relaxation. To overcome this weakness, we propose a bilinear formulation for robust binary programming, which is as strong as theoretically possible. From this bilinear formulation, we derive strong linear formulations as well as structural properties, which we use within a tailored branch and bound algorithm. We show in an extensive computational study that our algorithm outperforms existing approaches from the literature by far. Furthermore, we show that the fundamental structural properties proven in this paper can be used to substantially improve approaches from the literature. This highlights the relevance of our findings, not only for the tested algorithms, but also for future research on robust optimization.

■ WC-20

Wednesday, 13:20-14:50 - ESA W(est) 119

Game Theory and Dynamics

Stream: Game Theory and Behavioral Management

Science

Invited session

Chair: *Daniel Schmand*

1 - Asynchronous Opinion Dynamics in Social Networks

Daniel Schmand, Petra Berenbrink, Martin Hoefer, Pascal Lenzner, Malin Rau, Dominik Schallmoser

We focus on a variant of the well-known Hegselmann-Krause model for opinion dynamics. Agents are connected by a social network and their opinions evolve in an iterative process. When activated, an agent adopts the average of the opinions of its neighbors having a similar opinion. By this, the set of influencing neighbors of an agent may change over time. We study the Hegselmann-Krause system with asynchronous opinion updates and an underlying social graph. We show that such opinion dynamics with random agent activation are guaranteed to converge for any social network. We provide an upper bound of $O(n|E|' (\epsilon/\delta)')$ on the expected number of opinion updates until convergence, where $|E|$ is the number of edges of the social network. Our results are a major improvement over the previously best upper bound of $O(n^9 (\epsilon/\delta)')$. Our bounds are complemented by simulations that indicate asymptotically matching lower bounds.

2 - Complexity of equilibria in binary public goods games on undirected graphs

Maximilian Stahlberg, Max Klimm

We study the complexity of computing equilibria in binary public goods games on undirected graphs. In such a game, players correspond to vertices in a graph and face a binary choice of performing an action, or not. Each player's decision depends only on the number of neighbors in the graph who perform the action and is encoded by a per-player binary pattern. We show that games with decreasing patterns (where players only want to act up to a threshold number of adjacent players doing so) always have a pure Nash equilibrium and that one is reached from any starting profile by following a polynomially bounded sequence of best responses. For non-monotonic patterns where players want to act alone or alongside a fixed number of neighbors, we show that it is NP-hard to decide whether a pure Nash equilibrium exists.

3 - Algorithms for Financial Networks

Martin Hoefer

The understanding and regulation of financial networks is an important challenge in modern societies. A central aspect in these networks is clearing, i.e., the result of debt resolution that determines the assets (and potential bankruptcy) of all involved financial firms. In recent years, there has been a surge of interest in algorithms to improve the clearing properties in financial networks. This talk will survey some of our recent work in this area on local optimization and game-theoretic approaches.

4 - An Ascending Auction for Computing Minimal Walrasian Prices via the Matroid Partitioning Algorithm

Niklas Rieken, Katharina Eickhoff, Britta Peis, Laura Vargas Koch, Laszlo Vegh

Determining prices on a market where a seller aims to sell a finite set of indivisible distinguishable goods to a finite set of buyers is a well-studied problem with countless applications. Prices on the items are called Walrasian prices if they admit an envy-free allocation of items to the buyers such that all items with positive prices are sold. Such Walrasian prices are guaranteed to exist if the buyers' valuations are gross substitute (GS), a concept introduced by Kelso and Crawford. A very natural process to determine prices of the goods is an ascending auction, where prices are raised step by step on overdemanded sets. Provided that all buyers have GS valuations, Gul and Stacchetti have shown that an ascending auction which iteratively raises prices on inclusion-wise minimal maximal overdemanded sets terminates with the (unique) componentwise minimal Walrasian price vector. While they did not focus on the computability of the price raising step, it is by now known that an inclusion-wise minimal maximal overdemanded set can be computed in each iteration of the ascending auction in polynomial time with tools from discrete convexity. We present a simple and purely combinatorial polynomial time algorithm for their computation: we show that the desired overdemanded sets can be computed using the exchange graph of the classical matroid partitioning algorithm. Moreover, we show that for GS valuations the component-wise minimal prices that admit an envy-free allocation are the same as the minimal Walrasian prices. This enables us to show a very natural monotonicity of minimal Walrasian prices with respect to changes in supply and demand. More concrete, we show that the minimal Walrasian prices can only increase if supply decreases, or demand increaseses.

■ WC-21

Wednesday, 13:20-14:50 - ESA W(est) 122

Financial Modeling

Stream: Financial Management and Investments
Invited session
Chair: *Sebastian Golder*

1 - The effects of labor choice on investment and output dynamics

Haejun Jeon, Xue Cui, Chuanqian Zhang

We incorporate both labor and capital as production inputs and discuss the effects of labor choice on a firm's optimal investment decision and output dynamics based on real options framework. In particular, we introduce different levels of labor flexibility and examine how it affects the firm's investment and employment strategy. We show that upward-only adjustable labor, which can arise from employment protection, discourages investment and makes a negative short-run impact on labor employment but a positive impact in the long-run. We also show that the firm invests earlier and produces more at the investment timing when it is either highly labor-intensive or highly capital-intensive. However, the impact of labor share on output changes over time; it is more pronounced over time when labor is fully flexible or upward-adjustable but less pronounced with downward-adjustable labor. Furthermore, we show that uncertainty can make both positive and negative impacts on investment, but that the latter is more pronounced when the labor share is high.

2 - Continuous-time optimal execution under a transient market impact model in a Markovian environment

Makoto Shimoshimizu, Masaaki Fukasawa, Masamitsu Ohnishi

We analyze a continuous-time optimal trade execution problem under a transient market impact model. We also consider the effect of what we define as Markovian environment on the optimal execution strategy through price process.

Our problem is formulated as a stochastic continuous control problem over a finite horizon of maximizing the expected utility from the final wealth of a large trader with Constant Absolute Risk Aversion (CARA) von Neumann-Morgenstern (vN-M) utility function. By examining the Hamilton-Jacobi-Bellman (HJB) equation, we characterize the optimal trade execution strategy and its associated optimal value function. The trade execution strategy is shown to be a time-dependent affine function of three state variables: the remained trade execution volume of the large trader and, so-called, the residual effects of past price impacts caused by the large trader, and the Markovian environment. Further, the time-dependent coefficients could be derived from a solution of a system of ordinary differential equations (ODEs) with terminal conditions, which is numerically tractable.

3 - CSR Investment Timing in a Duopoly: The Threat of Responsibility Violations in the Context of Socially Conscious Consumers

Stefan Kupfer, Elmar Lukas

Addressing social and environmental problems is increasingly important, but is still a challenging problem in business practice. We use a real options model to analyze the strategic decision of two competing firms in a duopoly to time their investment in responsible operations to examine why some firms engage in responsible operation early while others delay their commitment. The underlying trade-off is that companies can choose a responsible but more costly operation, or continue with cheaper normal operation as has been used in the past, but indirectly accepting potential violations of social and environmental responsibilities. If a firm has not switched to responsible operation and there is public backlash, the firm faces an increase in costs and loss of customers. The reason are two different types of customers: While normal customers are indifferent to the CSR strategy, socially conscious customers evaluate non-responsible activity negatively. The second type may be lost and exit the market completely or switch to the other firm, if it has adopted a responsible strategy. We investigate why and when firms choose to adopt a responsible strategy, and which profit-maximizing equilibrium strategy emerges as a result of the investment required to do so. We derive the optimal timing strategy for both firms under different market structures and analyze how the threat of a potential CSR violation, the share socially conscious customers and the difference and operating costs impact the investment strategy. We find that traditional and thus cheaper business models represent opportunity costs for investing in CSR activity. Furthermore, we analyze the impact on firm value and derive welfare implications.

4 - Present Bias and Mortgage Refinancing Decisions

Sebastian Golder

Refinancing a mortgage is one of the biggest financial decisions for many households. While recent literature documents that households often fail to refinance their mortgages optimally, little is known about the underlying determinants for this behavior. Studies on other financial decisions suggest that households are present-biased when choosing between immediate and delayed costs or rewards. Since refinancing a mortgage is essentially a trade-off between refinancing costs today and potential interest savings in the future, the question arises whether present bias causes the suboptimal mortgage refinancing behavior. To address this open question, I study the optimal mortgage refinancing problem of a behavioral household who is present-biased and inattentive to mortgage rates. In solving the problem, I derive the first closed-form optimal refinancing rule of a behavioral household, enabling the estimation of the model. I estimate the model based on Danish administrative data, showing that it can endogenously explain delays in mortgage refinancing. I find substantial evidence of present bias of households, with the average household having a short-run discount factor of beta=0.39. Older, less-educated, financially wealthier, and higher-income households exhibit stronger present bias, whereas higher housing wealth and financial literacy reduce this behavioral bias. Implications for the refinancing channel of monetary policy transmission are discussed.

■ WC-23

Wednesday, 13:20-14:50 - ESA W(est) 222

Assembly Line Balancing and Warehouse Control

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *Celso Gustavo Stall Sikora*

1 - Solving the Assembly Line Balancing Problem with LocalSolver

Léa Blaise

This talk will show how the algorithms implemented in LocalSolver, taking advantage of its set-based modeling, make it a solver of choice for solving the Assembly Line Balancing Problem, as well as other problems with similar structures. We will present a new local move integrated into LocalSolver's local search component, applicable to any packing problem: it is automatically activated when the model involves capacity constraints on set variables. This move is based on ejection chains: it consists in a series of element transfers from one set variable to another. It helps LocalSolver get out of local minima, in which the values of many set variables need to be modified for the solution to be improved, by rearranging the elements contained inside k set variables so as to empty one of them. It is particularly useful on the most combinatorial and most challenging packing instances. We will show how the integration of this local move enables LocalSolver to obtain very good performance on the Assembly Line Balancing Problem. We will give numerical results on the "very large" benchmark from [1], comprising more than five hundred instances of one thousand tasks. We will show that LocalSolver not only clearly outperforms CP Optimizer and MIP solvers, but also improves the literature's best known solution on 59% of these instances. We will also show that the integration of this new move into LocalSolver's local search improves its performance on other problems, such as the Bin Packing Problem.

Reference [1] A. Otto, C. Otto, and A. Scholl. Systematic data generation and test design for solution algorithms on the example of SALBP-Gen for assembly line balancing. European Journal of Operational Research, 228(1) :33-45, 2013.

2 - A Supervised Machine Learning-based Metaheuristic for the Joint Order Batching and Single Picker Routing Problem

Murwan Siddig, Stefan Bomsdorf, Michael Schneider

Order picking is the process of collecting multiple items using a picking cart in a warehouse. The Single Picker Routing Problem (SPRP) aims to find a minimum tour cost for collecting the items. The Order Batching Problem (OBP) aims to group multiple orders into distinct batches to minimize the combined cost of all picking tours without exceeding the picking cart capacity. The Joint Order Batching and Single Picker Routing Problem (JOBSPRP) integrates the SPRP and the OPB. We present variants of the Adaptive Large Neighborhood Search and Tabu Search (ALNS/TS) heuristic, introduced by Žulj et al. (2018), that leverage supervised machine learning (SML) techniques to solve the JOBSPRP. We provide preliminary results from our numerical experiments and discuss insights about the performance of our proposed SML-based ALNS/TS approach.

3 - Incorporating car-sequencing rules in the planning of mixed-model assembly lines

Celso Gustavo Stall Sikora, *Lorenzo Tiacci*

The assembly line balancing problem (ALBP) is a critical issue in the manufacturing industry, where the goal is to assign tasks to workstations in an assembly line to minimize the cycle time while maintaining balance among the workstations. The problem becomes more complicated in the context of mixed-model assembly lines where multiple products are assembled on the same line, and the sequence of products needs to be considered.

To address this challenge, our approach incorporates car sequencing rules, which are a set of constraints that dictate the sequence of products based on the presence of specific components. In particular, we consider a partially random sequence of products, respecting the H:N form of car sequencing rules, where at most H products with a specific component can be planned in any sequence of N products.

In addition to task assignments, our approach involves selecting the best sequencing rules from a finite set of options. This rule selection process can have a significant impact on the efficiency of the assembly line. We evaluate cycle time using a simulator and utilize a genetic algorithm to find solutions to the problem.

■ WC-24

Wednesday, 13:20-14:50 - ESA O(st) 120

Agent-based Simulation and Stochastic Optimization

Stream: Simulation, Reinforcement Learning and Quantum Computing
Invited session
Chair: *Christian Stummer*

1 - Better than Bass: An Agent-based Simulation of Innovation Diffusion

Theresa Elbracht, *Christian Stummer*

During the past few decades, studying the market diffusion of innovations has been a vivid field of research. One of the most influential models in Management Science is the seminal Bass model. It describes the spread of an innovation in a market as a contagious process that can be represented through a differential equation formulation with just three parameters. However, the simplicity of the model has its drawbacks. In particular, the Bass model implies that consumers are fully connected, meaning that each consumer is directly linked to all others, and that they are homogenous regarding their innovativeness and propensity to conform with others. Both assumptions capture the complexity of real consumer markets only to a limited degree. Our research exploits the strengths of a modern agent-based modeling approach in two ways. First, we connect consumers more realistically through a social network. Second, we allow for heterogeneity among consumer agents by drawing individual consumer attributes from a normal distribution around the population's mean values. To evaluate the effectiveness of our approach, we utilized the original parameters from Bass' application examples and compared the outcomes of our computational simulation experiments with the corresponding actual sales data. Our findings demonstrate that incorporating a realistic social network and consumer heterogeneity improves the prediction of innovation diffusion. We present the experimental setting and the simulation results.

2 - The Role of Uncertainty in Innovation Diffusion of Radically New Products: An Agent-Based Simulation Study

Frederik Tolkmitt, *Christian Stummer*

When consumers are uncertain whether they have sufficient (unambiguous) information regarding a new product, they might delay the adoption decision to a later point in time. This uncertainty effect can have a major impact on the market diffusion of an innovation. Most prior models that account for consumers' belief updating in such a setting capture this effect by resorting to some form of Bayesian learning and, usually, assume that the distribution of all possible information with respect to the attributes of the new product is normal and that the pieces of information received by individual consumers are independent draws from this distribution. Consequently, consumers' uncertainty regarding their beliefs decreases with each additional piece of information (e.g., after talking with a peer or being exposed to advertisements). This strong assumption is convenient as it makes models of opinion dynamics analytically tractable, and it works in many instances. However, when two diverging opinions are prevalent among consumers in a certain market and, thus, receiving additional information potentially increases uncertainty of individual consumers, a different approach is required. Radically new products, for which consumers cannot lean on previous experiences, constitute a prime example for such markets on which the distribution of beliefs can be bimodal. We propose a suitable approach that can deal with the latter setting and we demonstrate the value added of this novel approach (in contrast to the traditional approach) through computational simulation experiments based on an agent-based market model of innovation diffusion.

3 - Firm strategies for announcing the next generation of autonomous vehicles: An agent-based market simulation

Dirk Kohlweyer, *Herbert Dawid*, *Melina Schleef*, *Christian Stummer*

Producers of autonomous vehicles launch newer generations over time. As technology progress is uncertain, they can either announce the date of the next market introduction but cannot promise a certain performance level or vice versa. This constellation increases uncertainty on the part of consumers, who deal with such uncertainty in individual ways and, consequently, might opt to purchase a new autonomous vehicle, postpone the purchasing decision, or resort to purchasing a conventional vehicle. In our agent-based simulation study, we investigate the merit of the two above-mentioned announcement strategies. To this end, we set up a duopoly with two producers of autonomous vehicles, both relying on the same technology curve and each of them employing one of the two strategies. In several experiments, we vary the form of the technology curve as well as the degree of consumer heterogeneity, and we analyze the effect of the consumers' attitude toward uncertainty on market behavior.

4 - Rolling horizon production planning with forecast evolution based stochastic optimization

Manuel Schlenkrich, *Wolfgang Seiringer*, *Klaus Altendorfer*, *Sophie Parragh*

Production planning for multi-level manufacturing systems is a challenging problem in industry. In practice, optimization approaches that tackle this problem are integrated into planning frameworks in a rolling horizon manner, to consider parameter fluctuations and operative disruptions. Uncertainty is usually present in customer demand, as well as in system related parameters, such as setup time or resource capacity. Despite the reactive nature of rolling horizon planning, it is necessary to explicitly incorporate this uncertainty into the planning method. This is especially true for stochastic demands, because in multi-level systems, release of production lots for components needs to be anticipated several periods before the actual due date. In our work we integrate two-stage scenario based stochastic optimization into an event-based simulation environment, resulting in a rolling horizon simulation-optimization framework. We iteratively solve stochastic multi-item multi-echelon capacitated lot sizing problems considering current system state and demand forecast information. Customer demands are frequently updated, following the forecast evolution approach. We evaluate the stochastic approach and compare its performance to deterministic optimization, as well as to classical MRP. We perform an extensive simulation study testing several lead times, resource utilizations, safety stocks, demand updates and variation factors. We report important key performance indicators, such as the service level and overall production costs. Our approach outperforms both, deterministic optimization and classical MRP, on several of these

indicators, which shows that it can help to improve production planning in industry. This research is supported by Austrian Science Fund (FWF): P 32954.

■ WC-25

Wednesday, 13:20-14:50 - ESA O(st) 222

Assortments, Products & Markets

Stream: Pricing and Revenue Management
Invited session
Chair: *Rainer Schlosser*

1 - Group-constrained assortment optimization under the multinomial logit model

Julia Heger, Robert Klein

We study the retail assortment problem under the multinomial logit model with different types of group constraints, under which the products are attributed to exactly one or to several groups and there is a lower, upper or interval bound on the number of products offered per group or on the number of groups from which products are offered. The objective of such optimization problems is to maximize the expected revenue per customer while satisfying the considered set of group constraints. We formulate all optimization problems as binary fractional linear program and provide linear programming respectively mixed integer linear programming reformulations of the original problem that can be solved efficiently using state-of-the-art standard solvers such as Gurobi or CPLEX. We use these proposed group-constrained assortment problem formulations under the multinomial logit model to solve multiple practical industry use cases for the German car manufacturer BMW. These use cases include a variety of applications such as (1) the incorporation of diversity requirements concerning product categories, (2) the consideration of diversity requirements regarding product properties, (3) the prevention of dealer discrimination when selecting products to be offered in the assortment and (4) joint assortment optimization and pricing problems while adhering to further group constraints. We demonstrate that many of these types of problem settings can be considered jointly. Finally, we conduct an extensive numerical study and provide empirical evidence of the practical applicability of our approach even for realistically large problem instances.

2 - Price bundling considering flexible products, discrete customer segments and different types of capacity

Jacqueline Wand, Ralf Gössinger

In times of increased uncertainty, a more flexible resource utilization and the ability to customize can be beneficial for multi-product vendors. In this way, one possibility is to offer flexible bundles. Such a bundle is a package of different individual products sold at a single price, where at least one of the products is a flexible one. At the time of purchase, a flexible product is an incompletely specified offer, which contains a set of variants that meet the same customer needs. Its specification is completed in the time between purchase and delivery. The bundling of flexible products enables the vendor to manage capacity more efficiently. While price bundling makes it possible to achieve the capacity utilization with the highest expected profit at the time of purchase, flexible products provide opportunities to manage demand and resource uncertainties in the time between purchase and delivery. However, both price bundling and flexible products also have a significant impact on customers' purchasing behavior that is reflected in their WTP. Since this impact is essential for price and variant-related decisions, results of an empirical study on WTP for flexible bundles are used.

Against this background, we propose an extended optimization model that considers flexible bundles, multiple capacity types with different levels of product flexibility and multiple customer segments with different WTP distributions. The resulting MINLP model is solved by means of a standard solver. A full-factorial numerical study is conducted to analyze the model behavior in terms of solution time and solution quality. In addition, economic insights on profit, sales quantities and prices depending on characteristics of both customer segments and capacity are provided.

3 - Estimating Sales using Gaussian Processes

Alexander Kastius, Rainer Schlosser

Past research has shown that generalistic dynamic pricing using reinforcement learning can learn near-optimal pricing policies at the price of requiring a noticeable amount of observations. To overcome that limitation, we propose to represent the underlying functions using Gaussian processes instead. Gaussian processes can represent arbitrary functions and can require fewer observations than, for example, artificial neural networks. This comes at the price of costly inference. We use Gaussian processes for the representation of the dynamics of Markov decision processes, an overall assembly that aims at using the learned dynamics to estimate value functions and determine pricing policies. Especially competitor behavior and demand functions are considered elements of the process that determines the policy.

4 - Calibrating Synthetic Market Environments

Rainer Schlosser, Alexander Kastius

Many dynamic sales applications are complex and characterized by incomplete information. Developing effective and automated strategies for, e.g., pricing or ordering, is crucial but also highly challenging. While rule-based solutions are suboptimal and require expert knowledge, the use of dynamic programming methods that are based on forecasts is limited due to the curse of dimensionality. Alternatively, state-of-the-art reinforcement learning (RL) agents can deal with unknown and more complex environments but, however, require too much training to be applied in practice. In this paper, we discuss how to define suitable synthetic test environments to pre-train RL agents before releasing them to practice. For dynamic pricing examples, we study how a firm's historical data can be used to calibrate test environments mimicking real-life markets.

Wednesday, 15:10-16:10

■ WD-02

Wednesday, 15:10-16:10 - ESA B

Tutorial by AMPL

Stream: PC Stream
Tutorial session
Chair: *FIlipe Brandão*

1 - Large-scale optimization with AMPL in Python: Building optimization applications quickly and reliably, from prototyping to deployment
FIlipe Brandão

Python and its vast ecosystem are great for data pre-processing, solution analysis, and visualization, but Python's design as a general-purpose programming language makes it less than ideal for expressing complex real-world optimization problems. AMPL is a declarative language that is designed for describing optimization problems and that integrates naturally with Python. In this presentation, you'll learn how the combination of AMPL modeling with Python environments and tools have made optimization software more natural to use, faster to run, and easier to integrate with enterprise systems.

■ WD-06

Wednesday, 15:10-16:10 - ESA C

Semi-plenary talk Povoa

Stream: PC Stream
Semi-plenary session
Chair: *Martin Grunow*

1 - Driving Supply Chain Sustainability: The Crucial Role of Optimization in Achieving Sustainable Practices
Ana Paula Barbosa-Póvoa

In today's rapidly evolving scenery, the significance of sustainability has gained immense recognition, urging supply chains to embark on the journey towards building sustainable practices. Sustainable supply chains can be best described as complex networks of entities that oversee the management of products, encompassing suppliers, customers, and returns, while considering social, environmental, and economic objectives concurrently. However, the complexity of these systems poses a challenge in simultaneously addressing environmental and social goals alongside the traditional objective of profitability. To deal with these challenges, the development of decision-supporting tools for supply chain decision-makers is crucial. This talk focuses on the components of such tools, employing a systemic approach. Highlights the utilization of optimization-based models that effectively capture sustainability goals, considering the unique characteristics of supply chains. These tools enable the design and planning of sustainable supply chains, providing a solution that strikes a balance among economic, environmental, and social objectives. Furthermore, this talk identifies and discusses key perspectives and challenges associated with sustainable supply chains, which serve as catalysts for further research in the field. By delving into these aspects, we can foster a deeper understanding of the subject and inspire innovative approaches towards achieving sustainability within supply chains.

■ WD-07

Wednesday, 15:10-16:10 - ESA J

Semi-plenary talk Weber

Stream: PC Stream
Semi-plenary session
Chair: *Dominik Möst*

1 - OR-models for the energy transition - coping with uncertainty and heterogeneity
Christoph Weber

Energy and climate are hot topics for engineers, economists and policy makers. Not only the impacts of climate change are at the heart of societal debates but also the strategies for combating it. Operations Research can make important contributions to the latter debate - yet at the same time the complexity of the problems and the uncertainties surrounding them pose serious challenges to optimization approaches. The merits and pitfalls of linear, mixed integer, stochastic and convex non-linear optimization are therefore discussed with a focus on applications to German and European decarbonization strategies. Particular emphasis is given to the double interpretation of model results as optimal policy plans and as competitive market equilibria. Challenges arise thereby particularly when considering the multiple units and stakeholders of distributed energy systems - be it residential PV-battery systems, district heating grids or electric vehicles.

■ WD-08

Wednesday, 15:10-16:10 - ESA M

Semi-plenary talk Jozefowska

Stream: PC Stream
Semi-plenary session
Chair: *Florian Jaehn*

1 - Models for just-in-time scheduling
Joanna Józefowska

Just-in-time scheduling has many practical applications in manufacturing as well as in computing systems. The variety of applications results in many different models of just-in-time systems. Analysis of these models leads to interesting analogies and inspiring theoretical results that will be discussed in this talk.

Wednesday, 16:30-18:00

■ WE-02

Wednesday, 16:30-18:00 - ESA B

Decision Support for Production Planning

Stream: Decision Analysis and Support
Invited session
Chair: *Laura Wolf*

1 - An optimization-simulation approach for hardware capacity planning in cloud infrastructure under demand uncertainty
Laura Wolf, Patrick Jahnke, Stefan Nickel

Cloud computing and especially Infrastructure-as-a-Service (IaaS) are becoming more and more relevant in industrial applications. In IaaS, cloud providers offer customers resources such as compute, network and storage. From the provider's point of view, the question arises of how many physical resources are required to cover the uncertain demand, to achieve utilization targets and deal with fluctuating workload demand. This decision must be made from a midterm perspective due to increasing supply chain cycles. We propose a method for cloud providers to deal with this hardware capacity planning problem under demand uncertainty (CPCI_DU) in a network of existing worldwide distributed data centers. Based on an optimization-simulation loop, it is investigated at which data center which hardware configuration is needed. The decision problem is modeled as a two-stage stochastic optimization problem in which the hardware configuration at each location is determined considering different planning scenarios on a mid-term planning horizon. The evaluation takes place in a subsequent simulation, in which different demand scenarios are considered on an operational planning level to review the proposed hardware allocation for robustness. This optimization-simulation loop is executed until a prespecified stopping criterion is reached. The computational results conducted with CPCI_DU show a robust planning approach to deal with demand uncertainty in the hardware estimation and allocation problem.

2 - Awareness of social indicators in multiobjective production planning
Markus Hilbert

In recent years, sustainability in production planning, i.e., lot-sizing and/or scheduling, has become a common topic in the relevant scientific literature. Usually, a bi-objective production planning approach is taken and trade-offs between an economic and an ecological criterion, such as makespan and energy consumption, are studied in an appropriate production planning context. However, the social dimension of sustainability is often neglected because social indicators are difficult to capture in mathematical modeling and optimization due to their qualitative nature. In this talk, we want to raise awareness of social indicators in the context of operational planning. Therefore, we briefly review the relevant literature in production planning dealing with social indicators and discuss the inclusion of such indicators via a tri-objective production planning problem, studying trade-offs between an economic, an ecological and a social criterion. A multiobjective fuzzy approach is used to obtain the respective optimal solutions and thus derive a performance score for all three dimensions of sustainability in an operational context.

3 - Plant-wide master production scheduling in the automotive industry: A MILP-approach and a simulation study
Thorben Krüger, Achim Koberstein

In this paper, we propose a new approach for short term master production scheduling in the automotive industry considering an entire plant structure, its state and order due dates. Existing approaches largely neglect the plant state, plant structure and lead times and performance studies regarding suitability for realistic applications are often not available. To this end, we propose a volume-oriented short term master production scheduling approach, which considers the relevant plant parameters. Our approach provides decision support in selecting orders from an order pool to be produced next and to be assigned to the next shift of the first subsection of the plant, i.e., the body shop. To demonstrate the practical applicability and to evaluate the decisions suggested by our approach, we model a fictive but realistic plant using event-discrete material flow simulation. In our numerical studies, the simulation model represents the current plant state and plant behavior and an optimization model serves as a decision maker for the production program. In different scenarios, we show that our approach is able to anticipate the behavior of the plant well and thus makes decisions to minimize due date deviation costs while regulating shares of components in the inventory of the plant. We demonstrate that this is particularly important after component blockings, as otherwise high additional costs can arise due to rework or line stoppages.

4 - The Distributed Flow-Shop Scheduling Problem With Inter-Factory Transportation
Tristan Becker, Janis Sebastian Neufeld, Udo Buscher

Large manufacturing companies typically operate a production network consisting of multiple factories. For flowline manufacturing processes, this results in the distributed flow shop scheduling problem. In this problem, jobs must be assigned to one of multiple distributed factories with identical flow shops. After assignment, jobs have to be completed within their designated factory. We extend the distributed flow shop scheduling problem by allowing for the transportation of intermediate goods between factories. We assume that there is an option for transporting intermediate goods between factories after each machine. In case of transportation, jobs incur shipping times that depend on the distance between the origin and destination factory and delay further processing. The objective is to minimize the maximum makespan across factories. We propose an iterated greedy search procedure for distributed flow shop scheduling with inter-factory transportation. Computational studies demonstrate the effectiveness and efficiency of our algorithmic approach and provide insights into the value of transportation. Results indicate that transportation leads to better utilization of machines across factories by resolving bottlenecks, thus increasing the overall efficiency by reducing makespan.

■ WE-03

Wednesday, 16:30-18:00 - WiWi A, VMP5

Exploring Advances in Delivery Systems: Micromobility, Micro Depots, and Home-Delivered Services

Stream: Logistics
Invited session
Chair: *Dominik Stampa*

1 - Comparing Mobile and Static Micro Depots for Last-Mile Delivery
Dominik Stampa

Micro depots are a promising concept to improve parcel delivery on the last mile especially in urban areas. Parcels are brought to the micro depots by a larger truck and then delivered to the recipients with smaller vehicles, e.g. cargo bikes, which can be replenished at the micro depot throughout the day. We consider mobile micro depots, which can be relocated every day, and static micro depots. In the case of mobile micro depots, which are for example trucks or their trailers, we can choose positions for them depending on the actual delivery demand for this day. For static micro depots, we cannot do this, but need to set the positions once only without exact data of future delivery demand. We seek to analyze what advantages or disadvantages mobile depots bring with them compared to static depots, especially in terms of resulting route length and duration for the vehicle drivers delivering the parcels. To this end we model the placement of mobile depots as a location routing problem, whereas the delivery for static depots is solved as a two-stage problem: first, solving a location problem, and second, computing daily tours depending on the known demand. We generate small test instances of delivery demand for several days in urban areas based on real world delivery data, calculate heuristic solutions with algorithms from literature and compare resulting routes while varying parameters like the amount and capacity of mobile and static depots.

2 - Dynamic lot-sizing with imperfect production and rework of defectives
Steffen Rudert

Lot-sizing models are a vital part of the inventory management literature. Especially dynamic lot-sizing models are the basis of many industrial applications. Besides the basic single-item model, many extensions exist and among them, remanufacturing models are important concerning aspects of quality and sustainability. They focus on

the handling of product returns from customers and thus combine the processes of manufacturing and remanufacturing into a single model. While many models are focusing on this aspect of external product returns, comparatively little attention has been paid to internal product returns. Therefore, this paper introduces a basic model that assumes an imperfect production process and rework of the resulting defective items. We compare this model to the closely related models, namely the basic single-item model with perfect production and the remanufacturing model. In addition, a numeric study will compare the computation efforts for them and will also highlight hard cases of the rework model. It will be shown, that the model formulations are very similar but the computation times differ strongly for the three models thereby showing the largest runtimes for the rework model. Also, there are specific cost parameter combinations that cause multiples of the average computation times.

3 - Comparison and Generic Model Formulation of Home-Delivered Services
Esther Linner, Stefan Nickel

Many services in our day-to-day life are delivered to - or conducted at our home. Some typical home-delivered services are health care, deliveries of goods like parcels, food or groceries as well as repairs, cleaning or meals on wheels. All these services have similar planning characteristics on a daily basis: Clients need to be assigned to a service provider. For each of these service providers routes and schedules need to be designed. These tasks can be modeled as the Vehicle Routing Problem (VRP) with extensions. Most approaches in the literature account for only one of the previously named home-delivered services, including special extensions and tailored solution approaches. We compare the existing models of the different applications with respect to their different extensions and solution approaches. Finally, we propose a generic model formulation of the Home-Delivered Services Routing and Scheduling Problem (HDSRSP), that can cover multiple application scenarios. In order to show the applicability of these approaches to different scenarios, we test existing solution approaches on the generic model. We thereby analyze the influence of different extensions of the VRP on solution approaches and evaluate the ability to generalize the problem. In this way, we lay the groundwork for further research regarding general solution approaches for the HDSRSP.

4 - A Study for Determination of Micromobility Vehicle Stations Location in a University Campus
Süleyman Mete, Gülçin Boran

This study focuses on the determination of optimal locations for micromobility vehicle stations in a university campus. Micromobility has become increasingly popular in recent years, with electric scooters and bikes providing a convenient and eco-friendly transportation option for students and staff. However, without strategically placed stations, accessibility and convenience may be compromised. In this study, a location analysis was conducted on the optimal location and number of micromobility vehicles in University of Gaziantep by using the set covering and p-median location model. The models are solved by using the GAMS software. In the study area, 22 demand points and 22 potential station points are determined. Demand points (departments, dormitories, cafeterias, etc.) are the places where students and personnel are located mostly according to the student population. The results of the study provide valuable insights into the placement of micromobility vehicle stations in a university campus environment, with the aim of improving accessibility and promoting sustainable transportation options. The findings of this study can be used by university administrators, planners, and transportation officials to guide future decisions related to micromobility infrastructure and station placement.

■ WE-04

Wednesday, 16:30-18:00 - WiWi B1, VMP5

Exploring Advanced Planning and Optimization in Diverse Industrial Contexts

Stream: Logistics
Invited session
Chair: *Nadine Schiebold*

1 - Optimization of the spare parts supply for outstations in aviation industry
Nadine Schiebold, Theo Fischer

Due to its speed and reliability, the air cargo industry is essential in supply chain logistics and is constantly growing. Since this industry is globalized, global political events and disruptions in the world's supply chains directly influence air cargo. A cargo airline's aircraft must always be available to the company's network to be profitable and leverage its advantages. A lack of spare parts can cause aircraft to be grounded whenever an aircraft part fails, which makes spare parts management vital for the airline's success. To contribute to this essential task, we present a mixed integer model to optimally distribute spare parts at the outstations of a German air transport company. The objective function is a cost-based minimization of aircraft-on-ground situations where aircraft cannot deploy as planned and the schedule disrupts. The model is based on six-monthly flight schedules and previous spare part demand information. We compare the results with the company's spare part consumption in the second quarter of 2022 and investigate the integration of an additional outstation into the network. In addition, we include scenario analysis for outstation and home base parameters and limitations of the spare parts purchase quantity. We show that the generated solutions are suitable to support logistic planners and can be used to reveal problems such as lack of spare parts, insufficient storage space, or lack of workers. For example, if spare parts demand exceeds the hub's storage capacity in the future, high-traffic outstations will need to be better stocked with spare parts and take over planned repairs.

2 - A branch-and-price-algorithm for planning of rotor blade maintenance processes on onshore wind turbines
Martin Klingebiel

The planning of rotor blade maintenance processes on onshore wind turbines is part of the tactical pre-planning of a maintenance season. The problem is motivated by the case of an international operating onshore wind turbine manufacturer. The aim is to select and schedule the service teams of the service providers and internal teams for the maintenance of rotor blades such that the total costs are minimized and all services are covered. The sequence of the maintenance processes should be planned so that the capacities of the maintenance teams in particular are used in the best possible way, considering the legal, logistical and technical conditions. However, planning such a maintenance season is very challenging. For this reason, we formulate a mixed-integer linear problem for the routing and scheduling of service teams to perform maintenance activities at different locations with minimum total costs. To solve it, we propose a branch-and-price algorithm approach based on a Dantzig-Wolfe decomposition by service teams. The approach is implemented using the SCIP framework. We present the underlying problem decomposition, implementation, and some first numerical results.

3 - Framework for multi-objective analysis of port logistic scheduling and routing algorithms
Tibor Dulai, Daniil Baldouski, Balázs Dávid, Gyorgy Dosa, Miklós Krész, Zsuzsanna Nagy, Ágnes Stark-Werner

Finding efficient algorithms both for scheduling and routing trucks in the area of ports may reduce both the operational costs and the environmental impact, while it helps in optimizing the operation of related resources (e.g., cranes, ships, human workforce). We have designed and implemented a framework for the port logistic domain that allows the efficiency analysis of algorithms created to determine routing and/or scheduling of trucks. The framework is built on event-driven approach. The main components - that can be parameterized flexible - include a waiting queue outside of the port area, a pre-gate parking lot with finite capacity, gates and docks in arbitrary number and routes between them. The cost and capacity of each route can be set individually. The framework is able to handle the arriving trucks and ships and simulates their operation depending on the preset properties of the port and the constraints of the algorithm selected to analyze. We intend to present the overall framework, demonstrate its behavior through some examples and give an overview of our initial results on efficiency-analysis of truck scheduling and routing algorithms.

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4 - BinPacker Air: An Air Cargo Loading Problem
Katrin Heßler, Timo Hintsch, Lukas Wienkamp

We investigate a variant of the three-dimensional Variable Size Bin Packing Problem in which the bins have a special form of cuboid and non-cuboid unit load devices (ULDs). Furthermore, packing is constrained by additional practical restrictions, e.g., (non-)stackable items and avoiding floating packages. To solve the problem, a Randomized Greedy Search is presented. In each iteration, we call an insertion heuristic based on so-called extreme points, which are promising positions to load an item. We show that the generation of extreme points is quadratic in the number of items, and we extend the set of extreme points for non-cuboid ULDs. Moreover, an underlying grid structure is used to accelerate the collision and floating check while loading items. Computational results for randomly generated and real-life instances from the literature show the effectiveness of our method.

■ WE-06

Wednesday, 16:30-18:00 - ESA C

Retail operations

Stream: Supply Chain Management
Invited session
Chair: *Rob Broekmeulen*

1 - Integrated storage assignment for an e-grocery fulfilment centre
David Winkelmann

In this paper, we deal with a storage assignment problem arising in a fulfilment centre of a major European e-grocery retailer. The centre can be characterised as a hybrid warehouse consisting of a highly efficient and partially automated fast-picking area designed as a pick-and-pass system with multiple stations, and a picker-to-parts area. The storage assignment problem considered in this paper comprises the decisions to select the products to be allocated to the fast-picking area, the assignment of the products to picking stations and the determination of a shelf within the assigned station. The objective is to achieve a high level of picking efficiency while respecting station workload balancing and precedence order constraints. We propose to solve this three-level problem using an integrated MILP model. In computational experiments with real-world data, we show that using the proposed integrated approach yields significantly better results than a sequential approach in which the selection of products to be included in the fast-picking area is solved before assigning station and shelf. Furthermore, we provide an extension to the integrated storage assignment model that explicitly accounts for within-week demand variation. In a set of experiments with day-of-week-dependent demands we show that while a storage assignment that is based on average demand figures tends to exhibit a highly imbalanced workload on certain days of the week, the augmented model yields storage assignments that are well balanced on each day of the week without compromising the quality of the solutions in terms of picking efficiency.

2 - Behavioral Simulation of Blockchain-Enabled Market for Supplier Capacity Trading among Retailers
Arnd Huchzermeier, Kai Wendt

We study markets for trading supplier capacity among retailers facing random demands and varying goods valuations. Retailers buy claims on supplier's capacity before knowing their demand and trade them after demand realization. Two novel trading strategies emerge. Players, whom we call spot sellers, buy more claims than the maximum demand initially and sell excess to the market. Other players, whom we call spot buyers, buy few claims from the supplier, using the market instead. These strategies reinforce each other, reduce a player's demand risk, and contribute to the reduction of mismatch between supply and demand. In small markets, clearing prices are correlated with the product values and the net demand. But in large markets, clearing prices are anchored to the capacity reservation price and do not reflect either product values or the net demand.

3 - Store delivery planning for peak seasons in grocery retailing
Moritz Hundhammer, Heinrich Kuhn, Michael Sternbeck

Public holidays present significant challenges for grocery retailers, leading to a loss of delivery days and increased pressure on the supply chain due to higher consumer demand and costumer traffic. Retailers address these challenges by adjusting their weekly delivery patterns, adding extra shifts at distribution centers, and/or advancing order quantities from peak weeks to earlier weeks. The paper takes an integrative perspective, considering the cost implications and capacity constraints of all relevant stages of the intern supply chain of a grocery retailer, i.e., the distribution centers, transportation system and stores. We formulate the problem as a mixed integer program (MIP) that aims to minimize overall costs by orchestrating the aforementioned adjustment options during peak seasons. We solve the MIP model with Gurobi for instances of a large European retail chain. The results achieved offer valuable insights into the added value of tailored planning approaches for non-standard delivery periods.

4 - Scheduling store deliveries from an automated distribution center
Rob Broekmeulen

We consider a distribution center (DC) using order picking robots with an inflexible capacity to collect orders from grocery stores. Each store orders daily and gets its order delivered in the same time slot every day. The objective is to minimize the transportation costs, while respecting the required lead-time for the stores, the capacities of the DC and the delivery trucks. To solve the scheduling problem, we decomposed the problem in two subproblems. First, we cluster the stores into trips. This clustering results for each trip in a time window for leaving the DC, such that the delivery time windows of the stores in the trip are respected. The second subproblem sequences the clusters on the order picking robots, such that the timing and capacity constraints are respected. We applied the developed model to a case study of an European retailer and were able to produce feasible delivery schedules.

■ WE-07

Wednesday, 16:30-18:00 - ESA J

Value of Information

Stream: Continuous and Global Optimization
Invited session
Chair: *Dmitry Gromov*

1 - Comparing Incomplete Information and Rational Inattention in Games
Tommaso Denti

We systematically study the difference between exogenous information, structured information acquisition, and rational inattention. To do so, we fix a base game, which specifies the set of actions, payoff states, payoff functions, and the common prior over the state, and compare the set of payoffs and outcomes (i.e., action-state distributions) that each informational regime can induce. Under exogenous information, this set is characterized by the Bayes Correlated Equilibrium (Bergemann and Morris 2016). We show structured information acquisition attains the same outcomes but allows for lower payoffs from a given outcome. Hence, the welfare implications of an outcome can depend on whether the information generating it is acquired or exogenously given. Contrastingly, rational inattention can only cause outcomes that satisfy an additional separation constraint. However, this constraint never binds in generic games. Thus, for rational inattention to have a bite, one must either commit to a non-generic setting or impose restrictions on the underlying learning environment. For convex restrictions, we characterize when rational inattention refines the set of attainable outcomes and show that the refinement is dramatic whenever it occurs.

2 - The Nontrivial Role of Sample Information in Trust Problems with Bayesian Decision Makers
Michael Dreyfuss, Yahel Giat, Eran Manes

We model a generic trust problem that involves a trustor facing both systematic and specific uncertainty, as a hidden Markov decision problem. The problem we model represents many real-life applications of interest such as a bank-entrepreneur relationship and online shoppers and suppliers. Because the bank faces a safe alternative on each decision node, its problem involves a threshold rule in which as long as the perceived honesty of the entrepreneur is above the threshold, the bank agrees to fund the entrepreneur. We draw on the threshold property to

develop a novel decomposition of the effect of the model's primitives on steady state quantities and employ it to establish a counterintuitive relationship between the bank's profit and propensity to trust and the entrepreneur probability of running successful projects

3 - Value of Information: the optimal control perspective
Dmitry Gromov

Optimal control theory is a valuable tool for computing and analyzing optimal strategies in various fields, from economics to technology. However, applying optimal control methods to uncertain models can lead to incorrect conclusions, especially when modeling natural, social, or economic processes that inevitably include uncertainties due to incomplete knowledge of underlying dynamics, simplifying assumptions, and inability to measure parameters accurately. To make informed decisions, it is essential to understand and quantify the model uncertainty. The value of information (VoI) is a quantitative tool for decision-making under uncertainty. VoI analysis involves formalizing the process of obtaining new information about the model's structure or parameter values and quantifying the contribution of this information to improving predictions of the model's behavior. Next, the potential profit gained from the new information is qualitatively and quantitatively analyzed to make an informed decision about whether to acquire more information. This presentation will provide an overview of various approaches for formalizing the value of information. The discussion will cover the formal properties of VoI and present practical examples of its application.

4 - Evaluating Optimal Policy for Dynamic Resource Management: A Markov Decision Process Perspective
Prateek Verma

Natural resource management and biodiversity conservation are crucial but highly complex tasks that require careful consideration of a wide range of ecological and socioeconomic factors. Despite technological advancements, new management approaches are often hindered by uncertainties surrounding critical parameters and data availability. In this paper, we present a novel mathematical framework that evaluates the value of information and optimal policy for different resource management systems using Markov decision processes. Our approach addresses the gap in current research by applying the value of information approach to dynamic resource management problems. We offer a range of scenarios to assist decision-makers in adapting optimal policies using our method. Our study focuses on the management of rivers affected by eutrophication and algal bloom, demonstrating the practical application of our framework in computing algorithms under different conditions of observability and uncertainty. By using our framework, decision-makers can make informed and effective choices in natural resource management. Our study provides insights that are typically not possible through linear thinking and can assist in framing optimal policies for resource management. Overall, our research contributes to a better understanding of natural resource management and supports effective decision-making in this field.

■ WE-08

Wednesday, 16:30-18:00 - ESA M

Hydrogen and biogas networks

Stream: Supply Chain Management
Invited session
Chair: *Frank Meisel*

1 - Designing the hydrogen supply chain in Norway
Šárka Štádlerová, Peter Schütz

Hydrogen is considered a promising solution for decarbonizing the transportation sector, which is a crucial step towards meeting the CO2 emission reduction targets. Due to the non-existing hydrogen market, there is no supply chain available. A reliable hydrogen supply must be ensured to support the hydrogen transition. In our study, we address the problem of locating hydrogen facilities for the transportation sector in Norway. We formulate the problem as a multi-period facility location and capacity expansion problem with modular capacities to capture economies of scale in hydrogen production. Production costs depend on the capacity level and we define a specific convex piecewise linear short-term cost function for each capacity level. We consider two available production technologies, electrolysis and steam methane reforming with carbon capture. Due to the technological limitations of electrolysis, we model requirements on minimum production quantities. In our model, we allow only one capacity expansion during the planning horizon and do not allow for a technology switch. The objective is to minimize the total cost of investment, expansion, production, and distribution while ensuring that demand is met in each period. Given the complexity of the problem, we implement a solution method based on Lagrangian relaxation to solve the problem. Our approach is capable of designing the hydrogen infrastructure for the transportation sector in Norway using real-world data. Our results show that the initial demand for hydrogen is currently too low to build a steam methane-reforming facility. Instead, the optimal solution constructs only electrolysis facilities.

2 - Designing a Pipeline Network for Regional Biogas Supply Chains
Arne Heinold, Lisa Herlicka, Daniel Schröer, Frank Meisel, Uwe Latacz-Lohmann

In this talk, we explore the possibility of connecting several decentralized biogas plants via pipelines to a central upgrading plant. This network could support the balancing of fluctuations in renewable energy production from wind power or photovoltaic and it could be a new business model for plant owners to cope with expiring governmental funding.

The considered problem presents similarities with the minimal spanning tree problem but we allow for sub-networks and plant participation is not mandatory. We formulate this problem as a mixed-integer linear program, incorporating linearized investment and operating costs for edges and nodes, and maximize total profits using IBM's CPLEX solver. Due to the complexity and size of the problem, we employ a decomposition technique that assigns plants to clusters and solves each cluster individually.

We show results from a real-world case study in Northern Germany with more than 600 plants and compare different business models. Our findings demonstrate the general profitability of centralized upgrading that requires the building of a pipeline network between the plants and, therefore, the proposed solution might be a supportive approach to balance the supply and demand of renewable energy.

3 - Designing Diversified Import Networks for Green Hydrogen
Louis Vincent Sroka, Frank Meisel

Green Hydrogen that is produced with the help of renewable energy might be a solution to decarbonize the transport and energy sectors but poses a major challenge for some countries: their limited resources and production capacity will not suffice to match the high demands. Additionally, as recent events have made clear, a sustainable energy supply through imports is not only determined by cost and environmental aspects but also by factors like dependency on the exporting countries. Relying on a singular exporting country alone may cause political, financial, and moral complications that further hinder the achievement of a future sustainable energy economy. A large-scale hydrogen import, therefore, requires some sort of supplier diversification in the sense of avoiding strong dependencies. Our proposed optimization model determines an optimal diversified multinational transport network for the import of green hydrogen. We ensure diversification by setting a minimum number of export countries on the first (source countries) and on the last (transport to the importing country) level of the supply chain. Furthermore, transportation flows are limited for each transport link to reduce default risk. Within our model, we take transportation losses (boil-off) and conversion factors into account. We present computational results for a case study for hydrogen import to Germany, which illustrate how diversification impacts the sourcing and the total cost of such a diversified hydrogen import network. The overarching goal is to contribute to the efforts of establishing a sustainable import infrastructure for green hydrogen that is cost-efficient and provides a certain level of independence from exporting countries to ultimately decarbonize the energy and transportation sectors.

■ WE-09

Wednesday, 16:30-18:00 - ESA O(st) 221

Multi-objective Optimization

Stream: Continuous and Global Optimization
Invited session
Chair: *Fabian Chlumsky-Harttmann*

1 - Tracing locally pareto-optimal points by numerical integration

Lara Löhken, Kathrin Klamroth, Matthias Bolten, Onur Tanil Doganay, Hanno Gottschalk

We consider the problem of an approximation of the Pareto front of unconstrained multi-objective optimization problems.

Optimality conditions formulated for weighted sum scaralizations of the underlying problem yield parametric equations for Pareto critical points. The respective parametrization is given by the weights in the weighted sum scalarization.

Starting from one Pareto critical point, we can investigate its sensitivity with respect to parameter variations. This in turn leads to a description by differential equations. We can then trace the (convex parts of the) Pareto front by numerical integration, which yields an efficient and accurate approximation of the Pareto front.

In extension to previous results for the bi-objective case, we present preliminary results for the general multi-objective case. We discuss analytical results on the existence of solutions and preliminary numerical results for some test instances with three or more objectives.

2 - Non-convex shape optimization by dissipative Hamiltonian flows

Onur Tanil Doganay, Matthias Bolten, Hanno Gottschalk, Kathrin Klamroth

Shape optimization with constraints given by partial differential equations (PDE) is a highly developed field of optimization theory. The elegant adjoint formalism allows to compute shape gradients at the computational cost of a further PDE solve. Thus, gradient descent methods can be applied to shape optimization problems. However, gradient descent methods that can be understood as approximation to gradient flows get stuck in local minima, if the optimization problem is non-convex. In machine learning, the optimization in high dimensional non-convex energy landscapes has been successfully tackled by momentum methods, which can be understood as passing from gradient flow to dissipative Hamiltonian flows. In this article, we adopt this strategy for non-convex shape optimization. In particular, we provide a mechanical shape optimization problem that is motivated by optimal reliability considering also material cost and the necessity to avoid certain obstructions in installation space. We then show how this problem can be solved effectively by port Hamiltonian shape flows.

3 - Robust multi-objective optimization applied to a portfolio optimization problem

Fabian Chlumsky-Harttmann, Anita Schöbel

In our work we consider a multi-objective optimization problem with uncertainty in one objective function. The structure of the problem is inspired by the classical portfolio optimization problem – where an efficient portfolio that optimizes return, volatility and a number of other functions is searched for - but with the added complication that the volatility function depends on an uncertain parameter representing a finite number of different possible future economic conditions. We then aspire to determine solutions that are robust in a multi-objective sense. Research in recent years has proposed different robustness concepts for multi-objective optimization, such as minmax robust efficiency (Kuroiwa and Lee, 2012; Ehrgott, Ide and Schöbel, 2014) and multi-objective regret robustness (Groetzner and Werner, 2022). Finding such solutions for a general uncertain multi-objective problem, however, is hard. We investigate how this task gets easier by exploiting the special structure of our problem and use the problem discuss the meaningfulness and applicability of the known robustness concepts. Finally, we show that the different robustness concepts relate closely to each other given that the uncertainty is limited to one objective function.

■ WE-10

Wednesday, 16:30-18:00 - ESA W(est) 221

Machine Learning/AI

Stream: Choice Based Analytics
Invited session
Chair: *Martin Spindler*

1 - Causal Machine Learning / AI for Business Analytics

Sven Klaaßen, Martin Spindler, Philipp Bach

While machine learning and AI is mostly applied for prediction problems, which are correlation based, many interesting problems in business are so-called causal problems. Examples are dynamic pricing, resource allocation, targeted marketing and many more. The emerging field of causal machine learning combines causal inference methods with modern machine learning / AI. We will present the so-call double Machine Learning approach which allows for causal inference in high-dimensional settings. While this approach is getting very popular in industry and resarch, the practical implementation poses some challenges. We will give some guidance how to implement the approach, present simulation studies and highlight real world applications.

2 - Integrating machine learning methods into location planning under high dimensional MNL

Fiona Sauerbier, Simon Rienks, Knut Haase, Martin Spindler

Digitalization leads to large and complex datasets that can be used as input to optimization problems, especially choice-based optimization problems, which are usually combined with maximum likelihood estimation. Since this often leads to overfitting and unrobust optimization results in the high-dimensional case, we integrate several machine learning methods into this approach. First, we present an alternative to expert knowledge through data-driven preprocessing, using decision trees, and second, an estimation procedure of the utility function of the multinomial logit (MNL) model using maximum likelihood method in combination with a lasso penalty term. The data preprocessing is intended to linearly approximate possible non-linear utility components by using decision trees to binarily partition the collected covariates. In addition, interaction effects between several variables are included in the utility function. Since the function to be estimated contains many variables and possibly even more variables to be estimated than observations exist, the model may not be solvable using the classical maximum likelihood method. Therefore, we use the combination of the maximum likelihood method and a lasso penalty term. This leads to the fact that a unique solution can be estimated and variable selection is performed, thus avoiding overfitting. By combining this method, we present a procedure using a synthetic dataset for parcel shop location planning, which is intended to replace expert knowledge and still provide good and robust optimization results. Based on this, location planning is performed for the dataset. This approach provides better decision predictions and better optimization results compared to standard approaches.

3 - Towards Non-Parametric Random Utility Models for Recommender Systems

Thorsten Krause, Henning Gösling

Recommender Systems utilize choice data to bring users and relevant items together. Most modern recommender systems only consider binary feedback, i.e., whether a user interacted with an item or not. Few real-world systems and few publicly available datasets provide choice set information. But some practitioners have begun tracking choice sets and have integrated multinomial random utility models, which can increase accuracy and mitigate exposure bias. However, which random utility model the analyst should implement is unclear, and benchmarking different models is expensive. Instead, non-parametric density estimators for the random utility component could automatically learn the correct choice distribution. These are less commonly used in discrete choice analysis because of their slow convergence rate. But in recommendation tasks, data are often abundant. In this study, we integrate a non-parametric random utility model into a matrix-factorization-based recommender system and illustrate its goodness of fit on simulated data. We discuss the advantages and shortcomings of available non-parametric models for recommendation and outline future research directions. This study is, to our knowledge, the first to propose non-parametric random utility models for recommender systems. Non-parametric estimators could lift the need for expensive benchmarking, improve performance, mitigate exposure bias, and make discrete-choice-based approaches more accessible for recommender systems practitioners.

4 - Optimal learning for peer-to-peer transportation matching problems with supplier choice

Marlin Wolf Ulmer, James Bailey, Jennifer Pazour

We consider operations of a peer-to-peer transportation platforms, e.g., GrubHub for restaurant meal delivery. Over the course of the day, transportation demand reveals that needs to be satisfied fast. The transportation is performed by crowdsourced drivers (suppliers). In equidistant time steps, the platform matches transportation tasks with suppliers aiming for fast service for all current and future customers. Since the suppliers are not employed by the platform, they can decline matches, e.g., because they are too far away or because of pickup

and drop-off locations' characteristics. The preferences of individual suppliers are unknown to the platform, but information can be derived from their decisions. Since declined matches lead to delayed service, learning the preferences quickly can be quite valuable for the platform. Learning can be controlled by the platform's online decisions and there is a tradeoff between optimization and learning. Maximizing matching probability may lead to effective matchings now but little learning about the future. Maximizing learned information may lead to ineffective and unsuccessful matchings now but increases information and therefore matching effectiveness in the future. In this work, we propose a policy carefully balancing matching and learning effectiveness. We show that a slight sacrifice in matching effectiveness early may lead to significantly better overall performance.

■ WE-11

Wednesday, 16:30-18:00 - ESA H

Power grids and system resilience

Stream: Energy and Environment
Invited session
Chair: *Dominik Möst*

1 - A Tri-Level Approach for the Robust AC-OPF

Jorge Weston

In this work, we will focus on a robust approach that considers uncertainty of power loads in the alternating current optimal power flow (AC-OPF). Much of the current work related to robust AC-OPF makes use of convex relaxations or linear approximations to reduce the complexity of the problem. Moreover, many studies assume a feasible network response exists for the whole uncertainty set studied. However, both cases can translate into solutions that are not robust feasible, i.e., there may exist some uncertainty realizations for which the network cannot be operated properly. Here, we present an approach that models the robust AC-OPF as a min-max-min problem to (i) identify AC robust feasibility under power load uncertainty (discrete or continuous), and (ii) find a linear decision rule to model the network response once the uncertainty manifest itself. We solve the problem by solving the inner max-min with a spatial-branching approach together with cutting planes for the outer minimization problem. With this, a feasible robust solution can be obtained, if it exists. The spatial-branching algorithm has a finite termination that depends on the size of the uncertainty set and the given robust feasibility tolerance. Preliminary computational results, for small test cases of the IEEE library, show that the approach can detect robust infeasibility with a small number of iterations. However, solution times increase in case of robustness. From our results, with affine decision rules and box-type uncertainty sets, we notice that protection against the extreme points of the uncertainty set leads to a feasible solution that is robust for the whole uncertainty set.

2 - An Algorithmic Approach for the Generation of N-1-Secure Power System Test Cases

Oliver Gaul, Tim Donkiewicz

The optimal transmission switching problem (OTS) consists of finding a power system network topology that minimizes operating costs. To that end, switchable lines can be configured such that congestion is alleviated and cheaper generation units can be utilized. For the security-constrained OTS (SCOTS), solutions need to remain valid even in the case of unplanned unavailability of distinct network components. While there are widely used test sets for OTS (e.g., IEEE network test cases), most of the instances therein are infeasible for SCOTS. Modifying existing OTS test instances is common practice to obtain feasible instances for SCOTS-related research. These modifications are often undisclosed and differ between publications, which poses a threat to reproducibility and comparability. Additionally, researchers often only use a small number of instances to evaluate their methods, potentially as a consequence of the lack of publicly available feasible SCOTS test cases.

Within this presentation, we give an overview of how instances are modified in research and propose two algorithms that deterministically produce feasible SCOTS instances out of OTS-feasible ones.

3 - InnOpTEM: Integrated Optimization of Topological and Re-Dispatch Measures in Power Systems

Tim Donkiewicz, Oliver Gaul

Growing volatility in transmission systems, e.g., due to rising shares of renewable energy generation, can lead to increasingly challenging day-ahead network operation planning. With the amount of generated power at each generator already ordered ("dispatch"), operators need to ensure that power demand is met. Moreover, the network must operate within its technical limits and remain there in case of the unplanned unavailability of individual components ("N-1 security"). Operators can influence the network either by changing the power demand or generation using short-term measures ("re-dispatch") or by altering the topology of the network. The latter involves connecting and disconnecting lines at so-called bus bars, where sets of lines can be divided into disjunctive intra-connected subsets. The amount of required re-dispatch can be reduced by altering the topology. As re-dispatch measures are often comparatively expensive, topological actions can thus reduce the overall operation cost. Moreover, a combination of re-dispatch measures and topological actions can in certain be necessary to ensure a secure operation.

It is common practice for operators to plan re-dispatch and topological actions separately, which can lead to overall sub-optimal solutions. Within the InnOpTEM project, we develop methods for an integrated optimization of these problems. This presentation gives an overview of the current state of and challenges within the project.

■ WE-12

Wednesday, 16:30-18:00 - ESA K

Modelling electricity prices

Stream: Energy and Environment
Invited session
Chair: *Dogan Keles*

1 - An Electricity Price Modeling Framework for Renewable-Dominant Markets

Tobias Kargus, Martin Hain, Marliese Uhrig-Homburg, Wolf Fichtner

Renewables introduce new weather-induced patterns and risks for market participants active in the energy commodity sector. We present a flexible framework for power spot prices that is capable of incorporating a weather model for the joint distribution of local weather conditions. This not only allows us to make use of a long history of local weather data in the calibration procedure but also makes it possible to assess how changes in the renewable generation portfolio impact the characteristics of future wholesale spot prices. Empirical tests demonstrate the model's capability to reproduce salient features of market variables. We furthermore show why our model offers unique benefits for market players compared to existing approaches.

2 - Resilient Forecasting of High-Dimensional Network Time Series in the Energy Domain: A Hybrid Approach

Milena Petkovic, Janina Zittel

Energy systems are complex networks consisting of various interconnected components. Accurate energy demand and supply forecasts are crucial for efficient system operation and decision-making. However, high-dimensional data, complex network structures, dynamic changes, and disruptions in energy systems pose significant challenges for forecasting models.

To address this, we propose a hybrid approach for resilient forecasting of network time series in the energy domain. Our approach combines mathematical optimization methods with state-of-the-art machine learning techniques to achieve accurate and robust forecasts for high-dimensional energy network time series. We incorporate an optimization framework to account for uncertainties and disruptive changes in the energy system. The effectiveness of the proposed approach is demonstrated through a case study of forecasting demand and supply in a complex, large-scale natural gas transmission network. The results show that the hybrid approach outperforms alternative prediction models in terms of accuracy and resilience to structural changes and disruptions, providing stable, multi-step ahead forecasts for different short to mid-term forecasting horizons.

3 - Mitigating price risks for organizations' energy systems en route to net-zero using two-stage stochastic programming to consider uncertainty in energy and emission prices

Jessica Thomsen, Gregor Gorbach

Decarbonizing the energy systems of organizations is a crucial step towards a sustainable fu-ture. However, the design of decarbonization pathways can be challenging due to complexity and numerous uncertainties in the energy system environment. One approach to cope with high complexity is using optimization models. As real-world decisions cannot be based on per-fect knowledge and rather deal with a variety of different uncertainties, it is crucial to verify the robustness of model-based solutions. This work analyzes the benefits of using a two-stage stochastic programming (SP) method that considers uncertainty of future CO2 and energy prices, as important input parameters during the optimization process. The results of the SP approach are compared with the results obtained using deterministic optimization for a real-world energy system of an organization. The results underline that solutions generated by SP are more robust, with summed total cost deviation (STCD) for different scenarios not exceeding 52 %. In contrast, deterministic results have a deviation of up to 96 %. In general, this robustness to different price development pathways is achieved by installing a variety of energy generation technologies rather than se-lecting one to two technologies adapt for the given single price projection. Additionally, this work compares the robustness of SP for different optimization methods and assumptions (e.g., myopic vs. perfect foresight and green- vs. brownfield) and underlines that organizations should consider uncertain CO2 and energy prices to mitigate the risk of unfore-seen price developments. The findings have significant implications for organizations looking for cost-effective and robust decarbonization strategies.

4 - Online Power Plant Optimization and Dispatching on the Intraday Market

Alexander Franz, Peter Stomberg

The power intraday market (i.e., shortly before the physical fulfillment) is associated with considerable challenges. For example, the price information in the orderbook changes many times per second for various trading products. The volatility of these products can be immense because of the highly fluctuating, weather-dependent power production profiles and the uncertainty on the electricity market. Successful marketing of flexibilities like power plants requires an extremely active position management which must gather and process complex datasets from numerous sources. This is becoming an increasing challenge for power traders and system operators. Therefore, online optimization algorithms are crucial to ensure a reliable, resilient, and profitable operation of power plants. In this talk, an overview of the holistic optimization process will be given for a real-world, gas-fired power plant located in North Germany. The solution has now been in use for several years without active interventions of power traders or risk controllers. It is unprecedented in the much-cited "digitalization of the energy industry". The underlying mathematical model is a mixed-integer linear optimization problem. The target is to maximize the plant's profit by adjusting the plant's schedule for each quarterly hour of the intraday trading horizon with respect to its technical. This can be achieved by either increasing (i.e., selling on the market) or decreasing the plant's output (i.e., buying back on the market). Hence, continuous, non-negative variables are used for the power output, sell quantity, and buy quantity. Each type of the variables is limited by certain technical constraints (e.g., minimal / maximal power output) and market constraints (e.g., from the orderbook).

■ WE-13

Wednesday, 16:30-18:00 - ESA W(est) 121

Railway Optimization

Stream: Mobility and Traffic
Invited session
Chair: *Twan Dollevoet*

1 - A Heuristic Approach For the Real-Time Resolution of Multi-Occupancy Conflicts In Railway Nodes

Arturo Crespo Materna, Cedric Steinbach, Shanqing Chai, Hendrik Speh, Andreas Oetting

As an environmentally friendly means of transport, the railway occupies a key role in the transportation industry. To ensure operation safety, the railway infrastructure is divided into continuous block sections. A block section can only be occupied by one train at a time. The individual sequences of occupancies of the block section by multiple trains make up the schedule. During operation, the occurrence of stochastic events cannot be avoided. Most of them result in train journeys extending their occupancy time in specific block sections, and delaying their scheduled occupancies in following sections. If the occupancy of a block section shifts in such a way that it leads to a probable simultaneous occupancy of the section by more than one train, an occupancy conflict emerges. When such a conflict involves more than two trains it is called a multi-occupancy conflict. These conflicts are hard to resolve within nodes due to the enormous amount of possible resolution combinations and the number of follow-up conflicts they induce by their resolution. A first idea is to traverse all resolution combinations and choose the best alternative, which is time-consuming. To address this problem, we propose a heuristic approach based on our previous work that generates a subset of the traversed resolutions suited for each multi-occupancy conflict and chooses the most optimal resolution alternative. Additionally, to evaluate our approach we have developed a simulation platform that collects the operation environment information, identifies conflicts, and implements the resolution. Simulation results indicate that our approach requires less computation power compared to previous heuristics, and provides solutions with similar quality compared to traversing all resolution combinations.

2 - Risk-dependent scheduling of rail inspection runs and maintenance measures of rail defects

Maximilian Selch

The current maintenance strategy for rail infrastructure is based on preventive approaches with fixed inspection intervals. Based on eddy current and ultrasonic data recorded by rail inspection trains, the lines are evaluated for existing defects and their extent of damage. The necessary maintenance measures are then planned and carried out according to deadlines defined in specific guidelines. The goal is to transform maintenance management into a predictive strategy by determining the physical testability of the system used on the inspection trains based on statements about the capability to detect defects. This is done by probabilistically estimating the extent of possible undetected damage and predicting its growth over time. These risk indicators of the track sections to be inspected are used as stochastic constraints in a scheduling model to efficiently plan the deployment of rail inspection trains with the goal of minimizing the risk indicators and thus the probability of failures of the rail network. For the evaluation of the rail inspection data, an AI algorithm-based tool is developed, which automatically analyzes the data set based on characteristic defect images and outputs defects with a criticality value according to type and degree of damage. For this purpose, we present a scheduling model for bundled scheduling of derived maintenance tasks to minimize downtime, taking into account existing construction windows. For both scheduling problems, we present models and the results of test scenarios from the open digital test field of the German Centre for Rail Traffic Research.

3 - A Simple Policy for Fairness Over Time in Online Assignment Problems

Bart van Rossum, Rui Chen, Andrea Lodi

In addition to maximising efficiency, decision-makers are increasingly interested in obtaining solutions that are fair with respect to the utilities obtained by the different agents involved. One particularly relevant concept is that of fairness over time, where one is faced with repeated decision-making problems and wishes to obtain equity over multiple periods rather than within each period. We study fairness over time in online assignment problems, where a decision-maker is required to solve a new instance of a combinatorial optimisation problem in each period. An efficiency constraint models the tolerated loss in efficiency that may be used to obtain more equitable solutions. We assume that any solution to this problem can be partitioned into distinct pieces of work. In each period the work must be assigned to a fixed number of agents with the goal of maximising fairness over time. We provide a complexity and impossibility result, and study the theoretical properties of the intuitive 'best-to-worst' policy that assigns work to agents based on their accumulated utilities. We analyse the performance of this policy and the effect of the efficiency constraint in two extensive case studies. The first case study concerns the Crew Scheduling Problem and makes use of real-life instances from Netherlands Railways, while the second case study focuses on the Capacitated Vehicle Routing Problem and benchmark instances from literature. In both cases we consider both variable-sum as constant-sum utilities. Our computational results suggest that the best-to-worst policy effectively obtains fairness over time and that relaxing the efficiency constraint has a more

pronounced marginal effect on within-period fairness than on fairness over time.

4 - Fairness over Time in Railway Crew Planning
Twan Dollevoet, Bart van Rossum, Dennis Huisman

A recent trend in crew planning is to incorporate the preferences of employees and to consider fairness aspects of the resulting crew schedule. For example, the passenger railway operator Netherlands Railways (NS) applies the Sharing-Sweet-and-Sour rules in order to divide the desirable and less desirable work evenly over the different crew bases. However, the current approach has two drawbacks. First, it incorporates fairness only in the tactical planning stage, whereas this planning is adapted in the operational stage to deal with maintenance works and events. Secondly, it considers fairness at the crew base level, which might not ensure that work is divided fairly over individual employees as well. We tackle these two issues by formulating fairness requirements, based on the Sharing-Sweet-and-Sour rules, on the level of individual employees. Moreover, we incorporate these fairness considerations in the operational planning phase. Given that an operational plan is created for each day of the year separately, our methodology is related to the concept of fairness over time. In particular, we do not require the work to be divided fairly over the employees on each separate day, but over a longer period of time. We do so by developing a feedback mechanism that ensures that sufficiently much desirable work is assigned to each employee over the complete planning horizon. Our computational results demonstrate that our method succeeds in finding efficient and fair crew schedules for real-life instances of NS.

■ WE-14

Wednesday, 16:30-18:00 - ESA W(est) 120

Advances in transportation and logistics

Stream: Mobility and Traffic
Invited session
Chair: *Sandra Spiegelberg*

1 - Fare revenue forecast in public transport companies with different prediction methods: a comparative case study
Sandra Spiegelberg, Richard Hasenfelder, Nicki Lena Kämpf, Lucas Zaworski, Thomas Winter, Nicola Winter, Robert Knappe

We present the results of the research project ReComMeND focusing on fare revenue and ticket sales forecast for different public transportation companies. The data are based on monthly fare revenues and ticket sales for different product segments. The results will be transferred into practice in the follow-up research project ReComTrans with the goal of improving the process of revenue controlling by automated forecasts and by implementing and supporting data-driven decision-making in the existing controlling processes. We present prediction results derived from several different forecast methods like purely autoregressive methods such as ARIMA, SARIMA, and exponential smoothing as well as prediction methods that include exogenous variables. The data concerning exogenous variables are freely available and cover a wide range impact factors: tourism data, calendar data, population data, labor market development, weather and mobility data. We discuss the different methods and compare the prediction results based on common accuracy measures for the years 2019 - 2022 including the effects of the COVID-19 pandemic. In addition, we discuss the interpretability of the results and the performance of the different prediction approaches with respect to their implementation in the controlling processes.

2 - Using discrete optimization methods to build a geo-referenced microsimulation model
Kendra Reiter, Ulf Friedrich, Ralf Münnich

Microsimulation methods are an essential tool for analyzing the socioeconomic impacts of new policies, providing insights into mobility behavior, or studying demographic changes in a population. Knowing the exact geo-location of micro-units for different activities is crucial in creating detailed travel demand simulations. One detail of micro-units is their housing attribute. For this, the address selection problem aims to assign households to dwellings with precise geo-locations while preserving the statistical properties of the region. By leveraging the natural structure of this assignment problem, a maximum weight bipartite matching is formulated as a Mixed-Integer Linear Program. This model is tested on a synthetic dataset combining data from the 2011 German population and household census with a fully geo-coded building dataset for the city of Trier, Germany. Statistical restrictions are translated to soft constraints in the objective function, ensuring feasible solutions will also consider the fit between dwelling capacities and household sizes. The proposed model can be extended to incorporate additional constraints from various data sources and hierarchies, enabling geo-referenced analyses across diverse fields. Efforts are made to enhance runtime efficiency by tuning the implementation of the matching formulation, achieving a significant improvement. Comparisons with a classical Integer Linear Program approach demonstrate a promising potential of the proposed matching formulation, particularly when applied to the existing datasets.

3 - Stochastic Optimization of Worker Teams Formation and Routing for Airport Baggage Handling Tasks
Andreas Hagn, Rainer Kolisch, Stefan Weltge, Giacomo Dall'Olio

We address workforce optimization for baggage loading and unloading tasks, exemplary applied in the context of airport ground handling operations. Teams of skilled workers have to be formed and routed across the apron to unload the baggage from an aircraft after landing and to load it before take-off. Such tasks must be performed within time windows and, depending on the aircraft type, require a team of workers with different skill levels. Furthermore, travel times of teams are stochastic and given by empirical distributions. The objective is to find a plan that allows us to execute every task, is feasible for every possible realization of travel times, does not exceed the available workforce and minimizes the sum of expected task completion times. We formalize the problem by integrating team formation, hierarchical skills with downgrading, multiple trips, and different execution modes and incorporate stochastic travel times with a known probability distribution. We model the above problem as a mixed-integer minimization problem with robust feasibility constraints and chance constraints. We propose a solution approach based on branch-and-price and test it on real-world instances from a major European hub airport. The model is solved using column generation, where the pricing problem consists of a shortest path problem with resource constraints. We exploit several properties of the problem structure to improve runtime and convergence speed. Preliminary results show that the proposed algorithm is able to produce good or optimal results for small and medium and reasonable results for large-sized instances, likewise for small or medium-sized measurable spaces.

■ WE-15

Wednesday, 16:30-18:00 - R 0077, VMP5

Capacity planning in healthcare networks

Stream: Health Care Management
Invited session
Chair: *Sebastian Rachuba*
Chair: *Daniela Guericke*

1 - Collaborative Dynamic Hospital Capacity Allocation for and Steering of Pandemic Patients in a Region
Anne Zander, Stef Baas, Sander Dijkstra, Richard Boucherie

We consider a region with several hospitals collaborating to serve infectious patients during a pandemic in terms of allocating capacity to infectious patients and steering those to hospitals.

During pandemic waves, hospital capacity allocation to infectious and non-infectious (regular) patients must be adjusted dynamically. Freeing capacity for infectious patients, i.e., emptying regular rooms, takes some lead time. Therefore, we have to decide on preparing to open rooms for infectious patients ahead of time. We further assume that rooms can only be opened in a specific sequence, assuming a barrier between the infectious and non-infectious areas on a hospital floor.

We apply a direct lookahead approach, making use of short-time forecasts of infectious arrivals and bed occupancies. Specifically, we solve two rolling horizon stochastic programs to decide on the rooms to be opened or closed in each hospital and on steering regional infectious patients to hospitals per day. Here, we aim to balance costs for infectious overbeds, wasted capacity, and opening and closing rooms.

We compare the capacity allocation and demand steering strategy of our two stochastic programs with other heuristic strategies in a simulation study. In one strategy, hospitals decide on their capacity allocation individually. In another strategy, we assume a pandemic unit, where one hospital is designated to take all regional infectious patients, and the others will only start to admit patients when the pandemic unit is full.

Our numerical results show the benefit of cooperation and, specifically, the cost-effectiveness of using our stochastic programs to make decisions.

2 - Managing surgical waiting lists in a hospital network

Sebastian Rachuba, Mariana Oliveira, Lars Karbach, Daniel Santos

Hospitals and patients are facing growing waiting lists and backlogs for elective surgeries, resulting in long waiting times for patients that may negatively impact patients' health. In Portugal, patients are offered a voucher to transfer to a different hospital's waiting list once they reach 75% of their recommended maximum waiting time. While beneficial for the patients, such transfers can be costly for hospitals. In this talk, we consider a network of hospitals under a national health service. Regional agreements between hospitals to jointly manage their waiting lists can aid in reducing waiting times for patients. We use a combined simulation and optimisation approach to address the management of surgical waiting lists. The optimisation model determines regional agreements and patient allocation among hospitals, while the simulation model, capturing the evolution of demand, and evaluates resource utilisation and resulting waiting times. The overall aim is to reduce tardiness of scheduled patients and the costs associated with transferring patients between waiting lists. We present a case study using data from Portugal and Germany to illustrate the impact of waiting list management on key performance measures such as patient waiting time, hospital utilisation, and the number of transfers.

3 - Improvement Potential of Flex Nurses in the Neonatal Network

Gréanne Leeftink

Neonatology care, the care for premature and severely ill babies, is increasingly confronted with capacity challenges. The entire perinatal care chain, including the Neonatal Intensive Care Unit (NICU), operates at high occupation levels. This results in refusals, leading to undesirable transports to other centers or even abroad, which affects quality of care, LOS, and safety of these babies, and places a heavy burden on patients, their family, and involved caregivers.

Therefore, using Discrete Event Simulation with an integrated optimization module, we assess the improvement potential of network collaboration strategies that focus on reducing the number of patient transports, by allowing flexible deployment of nurses over the existing NICUs to match short-term changes in patient demand. A case study for the Dutch NICU network, involving 9 NICU locations and transportation of 15% of all NICU patients, shows the potential of transporting staff instead of patients: About 70% of patient transports can be eliminated in case of 15-50% capacity sharing, and about 35% of nationwide transports is eliminated with up to 15% capacity sharing in the Randstad conurbation area only.

4 - Cooperative solutions for capacity sharing in neonatal care

Daniela Guericke, Marieke Rikkert, Gréanne Leeftink

Neonatology care, the care for premature and severely ill babies, is increasingly confronted with capacity challenges. The entire perinatal care chain operates at high occupation levels. This results in refusals, leading to undesirable transports or alternate level care placements, which affects quality of care, length of stay, safety, and efficiency of involved stakeholders and resources. There is great potential improving capacity planning in the neonatal care chain, particularly when we consider the network of hospitals providing neonatology care. In this presentation, we assess the effects of cooperative solutions in a regional care network incorporating patient types with varying severity levels and arrival sources, as e.g. seen in medium-care units. We compare two approaches taking the three-patient-type model as a basis: a virtual pooled ward and a threshold-based patient referral policy. We use quantitative methods based on continuous-time Markov chains, heuristic optimisation, and discrete event simulation to assess the effects on overbeds, referrals, and rejections. A case study of a 4-hospital network in the Utrecht area shows the potential of a collective decline of 45 refusals per year and 35 overbed-days per year for the 4 medium-care unit neonatal care locations using the threshold policy.

■ WE-16

Wednesday, 16:30-18:00 - R 0079, VMP5

Algorithmic Advances in MIP and CP

Stream: Software for OR
Invited session
Chair: *Alexander Tesch*

1 - LazyCP - A Lazy Finite-Domain Constraint Solver based on Cutting Planes Reasoning

Alexander Tesch

In this talk, we introduce LazyCP which is a novel lazy finite-domain constraint solver. Unlike SAT-based constraint solvers that are based on resolution, LazyCP is based on the more general cutting planes proof system which allows for exponentially shorter proof deductions. To achieve this, LazyCP uses a fast home-built pseudo-Boolean (PB) solver as a core solving engine that interacts with the constraint solver by lazy constraint callbacks. A key component is that LazyCP explains propagations or conflicts by stronger PB constraints instead of only clauses which can generate stronger nogoods. We will present the main concepts of the solver and also give an overview of its performance on different problem sets from the SAT, PB, (M)IP and CP communities.

2 - Scylla: a matrix-free fix-propagate-and-project heuristic for mixed-integer optimization

Suresh Bolusani, Mathieu Besançon, Antonia Chmiela, Ambros Gleixner, Alexander Hoen, Gioni Mexi

A wide variety of real-world applications can be modeled as mixed-integer problems (MIPs). Despite the significant progress in algorithmic development, solving MIPs remains computationally expensive, particularly for large-scale and complex problems. Therefore, the development of effective primal heuristics is crucial. Traditional heuristics rely on iteratively solving linear problems (LPs) to obtain feasible solutions. However, solving LPs can still be computationally expensive, especially since an optimal solution might not always be necessary.

This work introduces Scylla, an LP-free primal heuristic for MIPs. Scylla uses matrix-free LP approximations with specialized termination criteria to derive integer feasible solutions via a parallelizable fix-and-propagate procedure, conflict analysis, and feasibility-pump-like updates to the objective function. Our results are promising, especially for instances where solving LPs is computationally expensive, and the start-of-the-art feasibility pump - a highly successful heuristic for solving MIPs - fails to find feasible solutions.

3 - Sparsity and sparsification of cutting planes, a computational study

Mathieu Besançon, Herman Appelgren

Cutting planes are valid inequalities for mixed-integer optimization that tighten the continuous relaxation. Adding cutting planes requires striking a balance between the strength of the node relaxations and their cost. In this work, we study the effect of the sparsity of cutting planes on the performance of branch-and-cut solvers, and present sparsification techniques that reduce the support of cutting planes while retaining their strength. Computational results show speed-ups on standard benchmark instances of both sparsity filtering and sparsification over the baseline cutting plane selection algorithms.

4 - Convex mixed-integer optimization with Frank-Wolfe methods

Hannah Troppens, Deborah Hendrych, Mathieu Besançon, Sebastian Pokutta

Mixed-integer nonlinear optimization encompasses a broad class of problems that present both theoretical and computational challenges. We propose a new type of method to solve these problems based on a branch-and-bound algorithm with convex node relaxations. These relaxations are solved with a Frank-Wolfe algorithm over the convex hull of mixed-integer feasible points instead of the continuous relaxation via calls to a mixed-integer linear solver as the linear oracle. The proposed method computes feasible solutions while working on a single representation of the polyhedral constraints, leveraging the full extent of mixed-integer linear solvers without an outer approximation scheme and can exploit inexact solutions of node subproblems.

■ WE-17

Wednesday, 16:30-18:00 - ESA O(st) 121

Combinatorial Optimization I

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Nele Pommerening*

1 - The k-median problems: a review

Nele Pommerening, Niklas Jost, Aleksandra Grochala, Uwe Clausen

The k-median problem is a popular NP-hard problem in discrete mathematics. The task is to select k centers such that the summed distance of any node to its closest center is minimized. In the literature, further details of the problem depend on the specific formulation. Especially, in some papers specific metrics are considered, the set of potential centers is the same as the set of nodes or the nodes are drawn randomly. We believe that seemingly minor differences between the formulations need to be stressed since algorithms for one model might not be adequate to be used for other formulations.

In addition, different techniques are used to solve this problem, as exact algorithms, approximation algorithms or heuristics. We will discuss the most important results of each technique, classify and survey k-median models. Furthermore, some recent trends of k-median problems will be presented. This paper is intended to illustrate the history of the problem and be a lookup for further research. The main goal is that the k-median problem papers with a specific problem formulation and/or solution method can easily be detected without reading any paper on the topic.

2 - Perfect Matching under Precedence Constraints

Corinna Mathwieser, Christina Büsing

Precedence constraints specify the order or sequence in which tasks or events must be executed or performed. They are commonly encountered in machine scheduling, where a job may not start unless its predecessor jobs have been completed. In the Travelling Salesperson Problem, precedence constraints are used to impose restrictions on the order in which vertices must be visited in a tour. This talk explores the use of precedence constraints in the context of perfect matchings. A perfect matching under precedence constraints is a matching in which the edges are ordered in such a way that no vertex is matched until its preceding vertices have been matched. We will discuss the computational complexity of perfect matching under precedence constraints. Finally, we will motivate and introduce generalized precedence constraints. These constraints allow for increased flexibility as they specify several predecessor sets to be associated with a vertex, one of which has to be covered by the matching prior to matching the respective vertex.

3 - On Constrained Weighted Edge Covers

Sven Krumke, Shai Dimant

We study generalizations of the Weighted b-Edge Cover Problem, in which one is given a graph and a coverage requirement for each vertex and the objective is to select a minimum-cost multi-set of edges such that the coverage requirement of each vertex is fulfilled.

In the first generalization, the Weighted b-Edge Cover with Colors, each edge is additionally associated with a color. Again the task is to cover each node a given number of times, but this time if an edge incident to a node is chosen, the node needs to be covered completely by edges of the same color. We show that, in general, the decision version of Weighted b-Edge Cover with Colors is NP-complete. However, the restricted version arising from a particular location covering problem (which motivated the study of the edge cover problem with colors) can be solved in polynomial time.

The second generalization we investigate is the Weighted b-Edge Cover with Bundle Constraints. Here, an additional input is a collection of edge subsets (bundles) and an upper bound for each bundle. The additional restriction is now that a solution may contain at most a specified number of edges from each bundle. We provide complexity results for this variant and show in particular that the corresponding decision version is strongly NP-hard, even if one only considers bundle constraints for triangles.

■ WE-18

Wednesday, 16:30-18:00 - ESA O(st) 122

Approximation Algorithms

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Nicole Megow*

1 - A PTAS for Minimizing Weighted Flow Time on a Single Machine

Andreas Wiese

An important objective in scheduling literature is to minimize the sum of weighted flow times. We are given a set of jobs where each job is characterized by a release time, a processing time, and a weight. Our goal is to find a preemptive schedule on a single machine that minimizes the sum of the weighted flow times of the jobs, where the flow time of a job is the time between its completion time and its release time.

It had been a long-standing open problem to find a polynomial time O(1)-approximation algorithm for this setting. In a recent breakthrough result, Batra, Garg, and Kumar (FOCS 2018) found such an algorithm if the input data are polynomially bounded integers, and Feige, Kulkarni, and Li (SODA 2019) presented a black-box reduction to this setting. The resulting approximation ratio is a (not explicitly stated) constant which is at least 10000.

We improve upon this result and present a polynomial time (1+eps)-approximation algorithm for the problem. The algorithm by Batra, Garg, and Kumar (FOCS 2018) reduces the problem to Demand Multicut on Trees and solves the resulting instances via LP-rounding and a dynamic program. Instead, we first reduce the problem to a (different) geometric problem while losing only a factor 1+eps, and then solve its resulting instances exactly by a dynamic program. In particular, our reduction ensures certain structural properties, thanks to which we do not need LP-rounding methods.

2 - Improved Approximation Algorithms for the Expanding Search Problem

Svenja M. Griesbach, Felix Hommelsheim, Max Klimm, Kevin Schewior

A searcher faces a graph with edge lengths and vertex weights, initially having explored only a given starting vertex. In each step, the searcher adds an edge to the solution that connects an unexplored vertex to an explored vertex. This requires an amount of time equal to the edge length. The goal is to minimize the weighted sum of the exploration times over all vertices. We show that this problem is hard to approximate and provide algorithms with improved approximation guarantees. For the general case, we give a (2e+epsilon)-approximation for every strictly positive value of epsilon. For the case that all vertices have unit weight, we provide a 2e-approximation. Finally, we provide a PTAS for the case of a Euclidean graph. Previously, for all cases only an 8-approximation was known.

3 - Matching Augmentation via Simultaneous Contractions

Felix Hommelsheim

We consider the matching augmentation problem (MAP), where a matching of a graph needs to be extended into a 2-edge-connected spanning subgraph by adding the minimum number of edges to it. We present a polynomial-time algorithm with an approximation ratio of 13/8 = 1.625 improving upon an earlier 5/3-approximation. The improvement builds on a new alpha-approximation preserving reduction for any alpha >= 3/2 from arbitrary MAP instances to well-structured instances that do not contain certain forbidden structures like parallel edges, small separators, and contractible subgraphs. We further introduce, as key ingredients, the technique of repeated simultaneous contractions and provide improved lower bounds for instances that cannot be contracted. Joint work with Mohit Garg and Nicole Megow.

■ WE-19

Wednesday, 16:30-18:00 - ESA O(st) 123

Multiobjective Optimization

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Michael Stiglmayr*

1 - Adapting Branching and Queuing for Multi-objective Branch and Bound

Michael Stiglmayr, Julius Bauß

Branch and bound algorithms have to cope with several additional difficulties in the multi-objective case. Not only the bounding procedure is considerably weaker, but also the handling of upper and lower bound sets requires much more computational effort since both sets can be of exponential size. Thus, the order in which the subproblems are considered is of particular importance. Thereby, it is crucial not only to find efficient solutions as soon as possible, but also to find a set of (efficient) solutions whose images are well distributed along the non-dominated frontier.

In this talk we propose modifications to increase the performance of multi-objective branch and bound algorithms by adapting the branching and queuing of subproblems. We use, e.g., the hypervolume indicator as a measure for the gap between lower and upper bound set to implement a multi-objective best-first strategy. We test our approaches on multi-objective knapsack (generalized) assignment and facility location problems.

2 - Ordering Cones for Ordinal Costs

Julia Sudhoff, Kathrin Klamroth, Michael Stiglmayr

Ordinal costs model the quality of elements of a combinatorial optimization problem whenever the quality cannot be measured by numerical values but can be associated with ordered categories. As an example the safety of a street for a cyclist can be ranked in ordered categories, like, e.g., safe (separate bike lane), medium safe (street with a bike lane) and unsafe (street without a bike lane). Ordinal costs are, for example, also applicable when quality, sustainability, olympic medals or school grades are modeled. In this talk, we show that ordinal optimization problems can be transformed into associated multi-objective optimization problems. The transformation exploits that ordinal optimality can be defined based on ordering cones. We present the ordering cone for ordinal costs and investigate the interrelation with the Pareto cone. Moreover, we analyze how the ordering cone changes, if we assume for example that each category is at least twice as good as the next-lower category.

3 - Enhancing Branch-and-Bound for Multi-Objective 0-1 Programming

Nicolas Forget, Sophie Parragh

In the bi-objective branch-and-bound literature, a key ingredient is objective branching, i.e. to create smaller and disjoint sub-problems in the objective space, obtained from the partial dominance of the lower bound set by the upper bound set. When considering three or more objective functions, however, applying objective branching becomes more complex, and its benefit has so far been unclear. We investigate several ingredients which allow to better exploit objective branching in a multi-objective setting. In particular, we extend the idea of probing to multiple objectives, enhance it in several ways, and show that when coupled with objective branching, it results in significant speedups in terms of CPU times. Besides, we generalize the best-bound idea for node selection to multiple objectives and we show that the proposed rules outperform the, in the multi-objective literature, commonly employed depth-first and breadth-first strategies. We test the proposed ideas on available benchmark instances for three problem classes with three and four objectives, namely the capacitated facility location problem, the uncapacitated facility location problem, and the knapsack problem. Our enhanced multi-objective branch-and-bound algorithm outperforms the best existing branch-and-bound based approach and is the first to obtain competitive and even slightly better results than a state-of-the-art objective space search method on a subset of the problem classes.

4 - Multiobjective shortest paths for multiobjective min. spanning trees and the k-shortest simple path problem

Pedro Maristany de las Casas

In recent years, multiple new algorithms for the Multiobjective Shortest Path problem have been published. Thereby, the size of instances that are solvable within a reasonable amount of time raised notably opening up new possible applications. In this talks, we consider two such applications. First we discuss a new dynamic programming approach to solve instances of the Multiobjective Minimum Spanning problem with more than two objectives. Then we use the recent Biobjective Dijkstra Algorithm and in particular it's asymptotic running time bound to design a new algorithm for the k-Shortest Simple Path problem with a running time bound that matches the one from Yen's classical algorithm for this problem. All algorithms perform well on big sets of instances from the literature. Implementations, results, and evaluation scripts are open source.

■ WE-21

Wednesday, 16:30-18:00 - ESA W(est) 122

Industry, Sales and Price Forecasting

Stream: Analytics, Forecasting and A.I.
Invited session
Chair: *Hans Georg Zimmermann*
Chair: *Sven F. Crone*

1 - Efficient and trustworthy sales forecasting for large industrial datasets

Alina Timmermann, Peter Buchholz

Sales forecasting in industrial companies is a challenge in times of rapidly changing environmental conditions that result in increasing uncertainty. Sales forecasting was based on expert opinions which are nowadays complimented or replaced by support software. Forecasting software has to provide results of high accuracy. Additionally, results must be trustworthy for the user to replace expert opinions as the standard. Each forecasting method performs individually well on different types of time series. Thus, decisions in companies with different products must rely on various forecasting methods due to the variety of time series. Therefore, the objective is finding the most appropriate method for each product. For fulfilling trustworthiness, providing a meaningful validity metric for the end user along the forecast is essential. In our work we propose an approach that, in a first step, divides products in groups by various clustering approaches. For each group and forecasting method, the expected prediction accuracy and runtime are estimated. Prediction methods with high accuracy and low runtime are selected for each group using Pareto optimization. In this way, the optimal forecast method can be derived for each product based on its group index. As a result of this approach, accurate, fast and trustworthy forecasts can be generated for large industrial datasets.

2 - High-dimensional high-frequency time series prediction with a mixed integer optimisation method

Nazgul Zakiyeva

We study a network functional autoregressive model for large-scale network time series. We approach the estimation of the proposed model using a Mixed Integer Optimisation method. By including the high-dimensional curves, the proposed model captures both serial and cross-sectional dependence in the functional time series network. We illustrate our methodology on a large-scale natural gas network data where our model provides more accurate several days-ahead hourly out-of-sample forecasts of the gas in- and out-flows compared to alternative prediction models.

3 - Uncertainty Quantification in Commodity Price Forecasting

Nico Beck

Commodity price forecasting is becoming increasingly popular as more commodities become tradeable. Because these prices are noisy and difficult to forecast, quantifying the uncertainty is important. Statistical models, such as Bayesian estimation models, can account for uncertainty. In recent years, recurrent neural networks have been increasingly used in this area. However, they typically ignore uncertainty and only predict point forecasts. Research has explored feedforward and convolutional neural networks to address this issue, but few studies consider the uncertainty of recurrent neural networks. To evaluate different approaches, we compare Monte Carlo dropout, Monte

Carlo drop connect, and an ensemble approach for historical consistent neural networks. The latter are recurrent neural networks that show promising results in predicting commodity prices. We evaluate the predictions in terms of accuracy, calibration of uncertainty, and quantile loss.

■ WE-22

Wednesday, 16:30-18:00 - ESA W(est) 220

Meet the Editors

Stream: PC Stream
Sponsored session
Chair: *Oliver Stein*

1 - Meet the Editors

Ulrike Leopold-Wildburger, *Oliver Stein*, *Guido Voigt*

We are delighted to invite you to attend our "Meet the Editors" event with Christian Stummer from Central European Journal of Operations Research, Oliver Stein from Mathematical Methods of Operations Research and Guido Voigt from OR Spectrum. The editors of the three Springer journals share insights on the aim and scope of their journals and talk in detail about the review processes. You are invited to ask questions.

■ WE-23

Wednesday, 16:30-18:00 - ESA W(est) 222

OR and the Global South 1

Stream: OR in Developing Countries
Invited session
Chair: *Gerhard-Wilhelm Weber*

1 - The Kerkenes Eco-Village Project in Turkey - revisited

Gerhard-Wilhelm Weber, *Francoise Summers*

One year ago, at OR 2022 Karlsruhe, we presented, considered and contributed to the Kerkenes Eco-Village Project on Turkish rural countryside. In this year of 2023, we will inform about new aspects and related developments and view this project also from the overall and national aspects of urbanization, energy supply and education in Turkey.

The purpose of the Kerkenes Eco-Center is to promote sustainability through environmental studies. It pursues the following objectives: - To advocate the use of renewable sources of energy; - To act as a stimulus and a catalyst for environment-friendly building with appropriate materials and energy efficient designs; - To act as a dynamic experimental base for testing designs, materials and activities suitable for viable and sustainable village life. - To encourage village development and income generating activities that might halt and even reverse migration from rural areas to the cities.

The Kerkenes Eco-Center Project was initiated in 2002 by G. and F. Summers from METU, Ankara, with the help of the Australian Embassy Direct Aid Program. By 2003 the concept of establishing an Eco-Centre devoted to research into and promotion of renewable energy and sustainable village life was developing. The aim was to halt, and even reverse, migration from rural areas to urban centers.

Around 10 years ago, G. and F. Summers gradually left METU and Turkey. We will reflect about this loss of connection of the developmental, scientific and ecological project with its recognized university.

Furthermore, we will relate the project with overall needs in Turkey, be it in the rural countryside or in the big cities, with regard to the demand for natural gas and for better primary school education in all social classes.

2 - A Novel Circular Economy Framework to Adopt Smart Waste Management System: Case Study of Istanbul, Turkey

Sadiye Eylul Sadanoglu

This paper presents a novel circular economy framework for the adoption of a smart waste management system in Istanbul, Turkey. Using a network analysis approach, the study maps out the flow of waste and resources in Istanbul's current waste management system, identifies critical points, and proposes a circular economy-based solution that leverages smart technologies to optimize waste collection and disposal processes.

The proposed framework integrates principles of circular economy, waste reduction, reuse, and recycling, with digital technologies such as the Internet of Things (IoT) and Artificial Intelligence (AI) to improve waste management. The framework includes a waste data management system, which tracks waste generation, collection, and disposal, and provides real-time information to stakeholders to optimize waste management processes.

The study identifies key stakeholders in the waste management system and their roles, including waste generators, collectors, treatment facilities, and policymakers, and evaluates the performance of current waste management practices. The network analysis reveals that the current waste management system in Istanbul is fragmented and lacks coordination, resulting in high transportation costs, low waste diversion rates, and environmental pollution.

The study concludes by discussing the potential benefits and challenges of implementing the circular economy framework for smart waste management in Istanbul. The benefits include environmental, social, and economic benefits, such as reduced greenhouse gas emissions, job creation, and resource efficiency. However, the challenges include the need for stakeholder engagement, financing, and regulatory support.

3 - LiBerated Social Entrepreneur: Using Business Metrics for Refugee Big Data Analytics with a Note on Ability and Disability

Berat Kjamili, *Gerhard-Wilhelm Weber*, *Dominik Czerkawski*

LiBerated Social Entrepreneurship in Developing and Emerging Countries involves social entrepreneurs using business metrics to sustain social impact. We explore the differences between developing and developed countries and introduce a new operational research (OR) approach to development. Commercial entrepreneurs focus on profit and revenue, while social entrepreneurs generate returns to society while aiming for sustainability. We apply Game Theory, Max-Flow-Min-Cut Theories, Schumpeter's creative destruction, and Adam Smith's diversification model to our business plan. Our project, Migport (formerly Q-Zenobia), utilizes "Refugee Big-Data Analytics" through a mobile application acting as a refugee portal. Refugees submit data via questionnaires to access verified news and opportunities. Additionally, we introduce Nshareplatform (NSP), which fosters better communication between the worlds of ability and disability, creating a friendly public space and personalizing assistance for people with disabilities. Our project benefits from Multivariate Adaptive Regression Splines (MARS), Conic MARS (CMARS), and its robust version RCMARS for Big-Data and Small-Data analytics. We aim to further support our joint and novel project.

■ WE-24

Wednesday, 16:30-18:00 - ESA O(st) 120

Mixed Integer Based Approaches

Stream: Project Management and Scheduling
Invited session
Chair: *Fabian Dunke*

1 - Set-cover master problem formulations in branch & price solution methodologies for optimal aircrew scheduling

George Kozanidis, *Odysseas Moschopoulos*

We consider branch & price solution methodologies for optimal aircrew scheduling. Such methodologies employ an optimization model termed master problem, which, given a set of pre-constructed crew rosters, aims to assign a particular one to each crew member of the group under consideration, so that a suitable aggregate objective expressing the total system cost is minimized. Driven by the requirement that the number of crew members assigned to each flight duty must always match the corresponding crew complement, the master problem is typically formulated as a set-partition optimization model. We propose its alternative formulation as a set-cover optimization model, in which

over-coverage of the flight duties is allowed, while roster quality is entirely ignored. The adoption of this modeling choice expedites significantly the identification of the attainable flight duty coverage, which is of utter importance for airline practitioners. This is due to the superior computational behavior of the set-cover model compared to the set-partition one, combined with the fact that the suppression of the roster quality cost reduces considerably the effort for identifying the optimal solution. To transform the optimal set-cover solution into an equivalent set-partition one, we utilize a mixed integer optimization model which removes suitably flight duties from the selected crew-rosters, so as to maximize roster quality without affecting optimal coverage. The key property that removing flight duties from a legal and feasible crew roster does not negate its legality nor its feasibility justifies the correctness of this approach. We report computational results from realistic problem instances demonstrating the behavior and performance of the proposed methodology.

2 - A MIP-based comparison of standard scheduling approaches for planning in additive manufacturing environments
Benedikt Zipfel

Additive manufacturing (AM), also known as 3D printing, enables the simultaneous production of different, complex, and customized parts directly from model data without prior tooling activities. These features allow manufacturers to respond quickly to varying customer demands and market trends. Furthermore, new opportunities arise in product design and innovation processes. In the early stages of AM, research primarily focused on developing and improving different AM technologies. However, research has also concentrated on production planning aspects emerging from these new technologies in recent years.

This study examines the implications of considering AM machines in scheduling approaches and evaluates the relationship to well-known scheduling problems on batch processing machines. To this end, we first analyze various AM technologies and derive ways to model the processing time of production jobs. Moreover, we examine the impact of integrating AM-specific processing time models into scheduling problems. For this purpose, we present a mixed-integer programming model aiming to minimize makespan on unrelated parallel AM machines. The model adapts principles from parallel machine scheduling as well as scheduling on batch processing machines. We compare different variants to calculate processing times for this model based on our findings and demonstrate the influences of AM on the scheduling tasks. To evaluate the performance of the model variants and their impacts on resulting schedules, we explore various instance settings. The results of our study highlight the benefits of explicitly incorporating AM features in problem formulations to substantially improve makespan in AM production facilities.

3 - A matheuristic for customized multi-level multi-criteria university timetabling
Fabian Dunke, Stefan Nickel

Course timetables are the organizational foundation of a university's educational program. While students and lecturers perceive timetable quality individually according to their preferences, there are also collective criteria derived normatively such as balanced workloads or idle time avoidance. A recent challenge and opportunity in curriculum-based timetabling consists of customizing timetables with respect to individual student preferences and with respect to integrating online courses as part of modern course programs or in reaction to flexibility requirements as posed in pandemic situations. Curricula consisting of (large) lectures and (small) tutorials further open the possibility for optimizing not only the lecture and tutorial plan for all students but also the assignments of individual students to tutorial slots. In this paper, we develop a multi-level planning process for university timetabling: On the tactical level, a lecture and tutorial plan is determined for a set of study programs; on the operational level, individual timetables are generated for each student interlacing the lecture plan through a selection of tutorials from the tutorial plan favoring individual preferences. We utilize this mathematical-programming-based planning process as part of a matheuristic which implements a genetic algorithm in order to improve lecture plans, tutorial plans, and individual timetables so as to find an overall university program with well-balanced timetable performance criteria. Since the evaluation of the fitness function amounts to invoking the entire planning process, we additionally provide a proxy in the form of an artificial neural network metamodel. Computational results exhibit the procedure's capability of generating high quality schedules.

■ WE-25

Wednesday, 16:30-18:00 - ESA O(st) 222

Capacity Control

Stream: Pricing and Revenue Management
Invited session
Chair: *Robert Klein*

1 - Demand Management for Parcel Lockers
Daniela Sailer, Robert Klein, Claudius Steinhardt

Parcel lockers are emerging as a viable alternative to traditional home delivery: When ordering goods online, customers can specify a locker instead of their home as their desired delivery address. Because the lockers are fully automated, they enable customers to pick up their parcels at any time within a given number of days. Therefore, customers benefit from increased flexibility in receiving their parcels. From the logistics service provider's point of view, parcel lockers offer a huge cost reduction potential resulting from consolidation and fewer failed delivery attempts. To fully exploit this potential and simultaneously ensure customer satisfaction, however, successful management of the locker's capacity is crucial. Basically, this requires that an appropriately sized compartment must be available for each customer's parcel from the time of delivery up until the customer collects their parcel from the locker. This is challenging because future delivery requests, the associated parcel sizes, and pickup times are stochastic from the provider's perspective. In this talk, we show that demand management may act as a valuable tool to maximize the number of served customers and effectively utilize scarce locker capacity. Firstly, we present the resulting sequential decision problem and highlight its main properties. Secondly, we outline an anticipatory solution approach. Thirdly, we conclude our talk with results from our computational tests that demonstrate the value of anticipation for this problem.

2 - Approximate Dynamic Programming Approach to Capacity Allocation in Remote Control Centers
Gideon Gottschalg, Arne Strauss

Low-latency telecommunication technology enables the teleoperation of heterogeneous vehicles (such as delivery robots, rental cars, mobile parcel lockers, airport luggage trucks, container shunting trucks etc) from a central remote control centre. These centres are currently being established in various countries and, as their operations will scale up to cover frequent requests from various vehicle types, they will encounter challenges with efficient allocation of teleoperators to requests.

This allocation process can be modelled as a Markov decision process with the aim to minimise (weighted) delays in the fulfillment of requests, accounting for different priority levels of different requests. For instance, moving a mobile parcel locker to a new position might be less time critical than getting a luggage truck to a landed aircraft on time. The main components of the system are the number and type of incoming heterogeneous requests as well as the number of operators in the control center. The requests differ in their priority, expected duration and completion deadline.

We tackle this capacity allocation challenge using an approximate dynamic programming approach. The results are compared with a number of intuitive heuristics in a simulation study to show that our new approach is able to improve performance significantly. Our approach also provides managerial insights to the key drivers of this new allocation problem.

3 - Network revenue management and fare proration revisited
Thomas Winter

Fare proration is one of the techniques applied in network revenue management. The motivation is to split the fare value of a multi-leg trip to the corresponding single flight legs during network decomposition to allow for a separate leg-based control and capacity optimization. We discuss and compare different fare proration techniques with respect to accuracy and convergence for some network scenarios. This includes simple proration technique like mileage proration as well as load factor based and bid price based proration methods.

4 - Risk-Averse Network Revenue Management

Martin Glanzer, *Christiane Barz*

Risk-averse revenue management models are important for businesses with insufficiently repetitive selling processes to rely on the averaging effect, and/or short-term revenue goals. The literature has recognized this need and offers a variety of models for single-resource applications, but not for the more challenging class of network problems. In this talk, we consider the network capacity control problem from the perspective of a risk-averse revenue manager. In particular, our objective is to determine acceptance policies, which adequately reflect risk-preferences instead of purely focusing on the expected revenue. To reflect a broad spectrum of risk-preferences, we consider an expected exponential utility maximizing revenue manager and formulate the corresponding sequential decision problem as a risk-sensitive Markov decision process. To overcome the curse of dimensionality, we build on a mathematical programming based approximate dynamic programming approach with a new multiplicative (monomial) value function approximation. Reformulating the resulting nonconvex approximate model as a signomial program and reducing the problem analytically, we present an efficient algorithmic solution. For a given degree of (absolute) risk-aversion, our algorithm determines a corresponding risk-averse acceptance policy. Policies generated by our algorithm resemble the popular structure of bid price controls and can decrease the revenue risk substantially in return for sacrificing only little expected revenue, as will be illustrated with numerical examples towards the end of the talk.

Thursday, 8:30-10:00

■ TA-02

Thursday, 8:30-10:00 - ESA B

Multi-objective optimisation approaches in energy system modelling

Stream: Decision Analysis and Support
Invited session
Chair: *Jonas Finke*

1 - An efficient solver for multi-objective onshore wind farm siting and network integration
Jaap Pedersen, Jann Weinand, Daniel Rehfeldt

Existing planning approaches for onshore wind farm siting and network integration often do not meet minimum cost solutions or social and environmental considerations. In this talk, we present an approach for the multi-objective optimization of turbine locations and their network connection using the Quota Steiner tree problem. We design an exact solver that makes large problem instances solvable and outperforms generic MIP solvers. Although our case studies in selected regions of Germany show large trade-offs between the objective criteria of cost and landscape impact, small burdens on one criterion can significantly improve the other. In addition, we demonstrate that contrary to many approaches for exclusive turbine siting, network integration must be simultaneously optimized in order to avoid excessive costs or landscape impacts in the course of a wind farm project. Our novel problem formulation and the developed solver can assist planners in decision making and help optimize wind farms in large regions in the future.

2 - Pareto Navigation for Multicriteria Building Energy Supply Design
Elisabeth Halser, Elisabeth Finhold, Neele Leithäuser, Philipp Süss, Karl-Heinz Küfer

Optimizing the energy supply design of buildings is an active area of research. This is not only because of financial incentives, which have become even more important in the last year, but also because of the climate crisis and the fact that buildings and their energy consumption are responsible for significant amounts of greenhouse gas emissions. Furthermore, it can be asked whether tolerance of small inconveniences can have a large impact on costs and carbon emissions.

The resulting optimization problem is therefore an inherently multicriteria one. However, finding an appropriate machine selection requires not only finding a trade-off between these conflicting objectives, but also incorporating an understanding of robustness to uncertainty into the model.

Using several years of heating and cooling demand data for an office building, we formulated the problem as an adjustable robust linear optimization problem.

The Pareto front is approximated using a sandwiching algorithm and further explored using Pareto navigation to find trade-offs visually.

3 - Generating alternative energy system design options that match real-world needs: the human-trained SPORES algorithm
Francesco Lombardi

Designing carbon-neutral energy systems is urgent, but many systems designs exist that are feasible and economically comparable on the way to this goal. In an attempt to discover such equally viable alternative system designs and let stakeholders explore their trade-offs, researchers increasingly rely on methods for 'Modelling to Generate Alternatives' (MGA) applied to energy system optimisation models. MGA methods allow for discovering a large sample of all the feasible designs for a given energy system with roughly the same cost. However, these equally valid design options are practically infinite for complex systems, raising the question of how best to use the available finite computational power when searching for them. Which design options are interesting for real-world decisions, and which are redundant? The answer to such a question lies with real-world stakeholder preferences and cannot be determined a priori.

To overcome this barrier, we propose a first-of-its-kind MGA approach that makes stakeholders part of the computational loop. More specifically, we devise a workflow where, first, stakeholders explore a first-guess sample of the viable design options and express their preferences. Second, an automated algorithm translates these preferences into parameters for the MGA search strategy. And third, alternatives are generated anew based on these human-trained search parameters, leading to more abundance of options in the region of the multi-dimensional option space where stakeholders were trying to find a consensus solution, and less so farther away from this region. We apply this novel humans-in-the-loop approach to our in-house SPORES algorithm for generating alternatives, and we demonstrate its effectiveness with a practical case study.

4 - Combining Pareto-front generating and diversifying optimisation methods for energy planning
Jonas Finke, Febin Kachirayil, Russell McKenna, Valentin Bertsch

Energy systems around the globe are undergoing a transformation towards an increased utilisation of renewable energy sources to mitigate climate change. This transformation involves complex decisions. Therefore, energy system models have been used for decades to support decision making in the energy sector. The use of multiple objectives in these models can significantly improve the decision support provided by reflecting the variety of existing interests.

Existing studies use a range of different methods typically following either of two approaches: (i) explicitly modelling multiple objectives to generate a Pareto front between them, for example the augmented epsilon-constraint method, or (ii) generating very diverse (in terms of system designs), near-cost-optimal solutions to implicitly find solutions that are appealing in terms of unmodelled objectives, for example Modelling to Generate Alternatives. Both approaches differ in what objectives they can incorporate and what research questions they can address and have so far only been used separately.

In this paper, we therefore aim at combining the two approaches to utilise their individual strengths for energy planning. We bring together the augmented epsilon-constraint method to generate a Pareto front with Modelling to Generate Alternatives to find diverse system designs within a specified region of that Pareto front. Using open data and the energy system optimisation framework Backbone, we model a sector-coupled energy system at district level. Using the combined methodology, we then optimise this system while considering a range of diverse stakeholder interests.

■ TA-03

Thursday, 8:30-10:00 - WiWi A, VMP5

Exploring Advances in Resource Optimization: Trajectory Planning, Clustering Techniques, and Cooperative Systems

Stream: Logistics
Invited session
Chair: *Andreas Geiger*

1 - Enhancing Supply Chain Coordination: A Comparative Analysis of Clustering Techniques for the Production Routing Problem
Andreas Geiger

Integrated planning systems can be used to better coordinate processes and better align decisions within supply chains. A system integrating the three key processes production, inventory, and distribution is called the Production Routing Problem (PRP). A single plant with capacity constraints produces a single product, which is distributed by a restricted number of homogeneous vehicles to meet retailers' demand. Due to periodic routing decisions combined with inventory and production decisions the PRP is difficult to solve. To overcome this issue, a set partitioning formulation based on predetermined routes is used. Different clustering techniques and a new heuristic approach are provided. To generate the set of routes, clusters are built using several clustering methods. For each of the generated clusters, a Traveling Salesman Problem (TSP) must be solved. To prevent unnecessarily

large TSPs from being solved, an upper bound on the route length is provided, based on vehicle capacity and demand patterns. Classical clustering methods considering distance only are tested. Other methods, considering periodic demand, such as a sweep-based clustering that incorporates random demand periods or a new clustering method based on demand and inventory information are also tested. Using these clustering methods to generate a set of initial routes to solve the PRP can lead to unnecessary retailer visits. Therefore, an improvement strategy is implemented, which identifies and removes those retailers. For further improvement, a local search, with respect to the vehicle load is applied. Computational tests are performed on benchmark instances from the literature to evaluate the heuristic and analyse the impact of the different proposed clustering techniques.

2 - HafenPlanZen: A tool for optimization and visualization of port planning decisions using simulation
Larissa Timm, Celso Gustavo Stall Sikora, Carsten Eckert, Ralf Sahling, Julia Hertel, Ulrich Baldauf, Justin Wilckens, Alwin Brehde, Leif-Erik Gorris

Maritime transport is vital to global trade, with ships carrying over 80% of the world's goods in volume. Efficient port planning is critical to the functioning of intermodal hubs like the Port of Hamburg, but long concessions of 20-30 years make port planning a complex and challenging task. A port is constantly evolving due to technological, economic, political, and environmental factors, requiring innovative approaches to port planning. Our project, HafenPlanZen, is a collaborative effort between the Hamburg Port Authority, Hamburg Port Consulting, and the University of Hamburg. The Port of Hamburg already has a high degree of digitalization and employs multiple digital twins to simulate and optimize various aspects of port operations. HafenPlanZen leverages this digital infrastructure and serves as a support tool for port planners, integrating data from multiple digital twins to provide a comprehensive overview of the port's behavior and efficiency. One of the project's key focuses is the development of a sophisticated 3D visualization tool that uses simulation to evaluate the performance of the port. HafenPlanZen's simulation-based approach enables port planners to test various improvement strategies and make informed decisions about optimizing port performance. The tool also provides improvement suggestions based on simulation results, allowing planners to make data-driven decisions about how to improve the efficiency and effectiveness of port operations. By utilizing the port's existing digital infrastructure, the project provides an innovative and efficient tool for port planning and optimization.

3 - Collision-free Trajectory Planning for UAVs with Velocity Dependent Energy Consumption
Christin Münch, Alf Kimms

To efficiently use unmanned aerial vehicles (UAVs) in last-mile delivery, we propose a MILP under a geometric viewpoint for collision-free trajectory planning for UAVs, emphasizing the problem of UAVs' limited range. The trajectory for one UAV contains position and velocity at a number of discrete time steps in an environment with obstacles. One customer is visited on the trajectory and launching/landing position are required to be on predefined line segments, representing streets where the UAV may be picked up, thus increasing the UAV's range. Additionally, we consider the energy consumption to be dependent on velocity as well as an upper limit on velocity. By making decisions about velocities, the range can be increased further. We present the MILP formulation as well as first computational results.

4 - Resource and cost allocation in cooperative two-tier city logistics systems
Johannes Gückel, Pirmin Fontaine, Teodor Gabriel Crainic

The rapid increase in urbanization and e-commerce leads to more goods that need to be transported within urban areas. While Logistic Service Providers (LSPs) seek to make transportation affordable and profitable, municipalities aim to promote a livable city and reduce negative externalities. A possibility to comply with both aspects are Cooperative Two-Tier City Logistics Systems (C2T-CLSs), in which LSPs cooperate to reduce both monetary and environmental costs. However, the questions about how to efficiently allocate resources and costs in a C2T-CLS are unanswered in academia and practice. We introduce a new tactical planning problem for the resource allocation in C2T-CLSs and present a new mathematical formulation that combines a service network design formulation on the first tier with a capacitated vehicle routing problem with release and due dates on the second tier. Our model accommodates different cooperation scenarios, such as full sharing of resources and customers, partial sharing of customers, and exclusive sharing of resources. This model is used in adapted cost allocation methods, including proportional methods and more complex game theoretical methods. To solve larger instances, we propose a problem-specific iterated local search metaheuristic that delivers high-quality solutions within short computing times. Within preliminary results, we show that simple proportional cost allocation methods (e.g., in proportion to the number of customers) easily violate basic fairness criteria. Allocating costs in proportion to the stand-alone costs of individual LSPs yields results similar to game theoretical methods. Furthermore, we find that through sharing only a small percentage of customers a high proportion of the potential cost savings could be achieved.

■ TA-04

Thursday, 8:30-10:00 - WiWi B1, VMP5

Exploring Advances in Logistics and Network Configuration: Benchmarking, Branch-and-Price, and Beyond

Stream: Logistics
Invited session
Chair: *Guillaume Crognier*

1 - The pi-transportation problem: On the value of split transports for the Physical Internet concept
Lennart Zey, Nils Boysen, Dirk Briskorn

The Physical Internet (PI) is a design metaphor that applies the digital internet as an archetype to rethink freight transportation in a more sustainable, interoperable, and collaborative way. Analogously to internet-protocols, freight should be encapsulated into standardized pi-containers and transported through a network of cooperating pi-hubs.

In spite of the analogy, however, even PI apologists admit that the parallels are not absolute: Digital data packages can be duplicated without cost, can be (re-)sent anywhere in short time, and generate no return flows.

In this talk, we focus on a characteristic of the digital internet that can be emulated by the PI but has not received much attention yet: split transports. Analogously to the internet-traffic, which forwards each data packet individually according to dynamically adapted routing tables, larger shipments can be split into multiple smaller pi-containers, so that different containers with the same destination may be routed via different paths.

We derive a basic scheduling problem, where a given set of (either split or unsplit) shipments aim to travel along a linear transport corridor with given pi-hubs. We formulate the so-called pi-transportation problem and present corresponding MIP-implementations. The latter are applied to evaluate the impact of split transports on the success of the PI concept.

2 - Branch-and-Price for a Service Network Design and Hub Location Problem
Alexander Helber, Marco Lübbecke

Less-than-truckload freight transport companies reduce transport costs of palette-sized shipments between customers by consolidating shipments at transshipment warehouses, also called hubs. To transport shipments between hubs, trucks operate a network of multi-stop line hauls, also called services. On a strategic level, companies need to plan where to locate hubs and which customers to assign to each hub. These decisions then impact the tactical design of the service network. In the literature these two aspects are usually considered separately or the service network design is strongly simplified. We propose a novel integrated problem that considers the service network design in more detail. Solutions to the integrated problem can lead to more cost-effective networks compared to optimizing both aspects individually.

The problem contains two challenging aspects that lead to large models. First, the number of potential services is large. Second, coupling the hub location and customer assignment problem to the network design problem usually requires significant numbers of variables and constraints. We implement a branch-and-price approach to deal with the large number of potential services. To handle the coupling, we discuss a potential Benders Decomposition approach. We present computational results for the performance of our algorithm. Additionally, we present a small case study on how the resulting networks of our approach differ from those obtained when optimizing the hub locations and the service network sequentially.

3 - Large scale inventory routing planning applied to gas transportation
Guillaume Crognier, Victor Kani, Lucas Ligny

A company specialized in gas production and transportation has to perform deliveries to its clients so that they never face any runout in their tanks. As the implemented solution has to manage both aspects of routing and inventory management, the corresponding problem falls in a particular version of the IRP problem. The size of the company instances (dozens of resources, hundreds of customers and hourly forecasts on planning horizon up to fourteen days) as well as the frequency of use (up to several times per day) force the solution to be fast and scalable too. Regarding resources, every driver can drive different tractors, which can itself be hitched to several trailers. Every "vehicle" is then a triplet of resources (driver, tractor, trailer). Each of these resources can have specific properties such as availability time-windows, speed and capacity. The triplets are not pre-determined: the optimization has to decide which resources are put together. The associated routing problem has a "many to many" structure, meaning several sources (to load trailers) and several customers (to perform deliveries) are taken into account. As all these places are not necessarily always opened, they also have their own availability time-windows. Eventually the underlying inventory problem is assumed to be deterministic. The telemetry measures sent from customers allow to forecast precisely enough their tanks levels. Deliveries must be made before these tanks run out of gas. The talk will present a solution to this problem based on local search, one of LocalSolver competitive edge technologies. Modelling choices as well as other specific business rules and results on large size instances will also be shown.

4 - Input-Output Mix Pattern Clustering with an Application to Performance-based Regulation of Electricity Distribution Service Operators
Mohsen Afsharian

We introduce a k-centroid clustering approach aimed at augmenting interpretability and streamlining the evaluation process within performance-based regulation. Through an optimization process, grounded in a mixed-integer program, entities are clustered based on their input-output patterns, which serves to reduce the complexity of the underlying estimated production technology. Our proposed method actively discourages the exploitation of extreme input-output combinations that could artificially inflate performance scores in practice. We leverage data from the electricity distribution sector to demonstrate the operationality of our developed method, and we compare the results with those obtained by the regulator's approach, where explicit ex ante weight restrictions are applied. This approach not only elucidates crucial trade-offs, thereby providing an optimization strategy for evaluating performance enhancement proposals, but it also empowers regulators with the ability to identify and rectify inefficient practices, such as high energy losses and excessive operational costs. The ultimate outcome is the promotion of a sustainable and efficient electricity sector.

■ TA-06

Thursday, 8:30-10:00 - ESA C

Fuel and CO2 networks

Stream: Supply Chain Management
Invited session
Chair: *Lisa Herlicka*

1 - A two-stage stochastic mixed-integer programming approach for the optimal design of a renewable fuel supply chain
Mina Farajiamiri, Jörn Meyer, Grit Walther

The production of renewable fuels using renewable resources like biomass, electricity from solar and wind power, and CO2 is a promising way to reduce GHG emissions in the transportation sector in all applications that cannot be electrified (i.e., long-haul trucks, aviation, and shipping). In addition to the challenges that are presented by the long-term horizon in line with the net zero emissions scenario and the seasonal availability of these resources, supply chain planning for renewable fuels is further complicated by the uncertainty of future demand. The aim of this study is to develop a two-stage mixed-integer programming model for optimizing the renewable fuel supply chain network under uncertain demand. The supply chain model accounts for a variety of factors such as long-term horizons, multiple periods, feedstock seasonality, multiple stages, and several conversion technologies. We select a total of four future scenarios to estimate future demand based on alternative roadmaps. The goal is to minimize the expected value of the total cost of the system. By solving this model, we will be able to determine the best possible solution (including investment decisions and resource utilization) that will incorporate all possible scenarios. We demonstrate the computational efficiency of the proposed model and approach by applying it to a real case study in the EU.

2 - Supply Chain Design for Carbon Capture and Storage in Northern Germany
Lisa Herlicka, Frank Meisel

In this talk, we focus on the development of a supply chain for a Carbon Capture and Storage (CCS) network in North Germany. Carbon Capture and Storage is a technology for capturing CO2 emissions from large sources, transporting the greenhouse gas to storage sites, and permanently storing it in underground geological formations. The supply chain for CCS includes the characteristics and capacities of the emission sources, various options for transportation modes and transport conditions of CO2, as well as injection specifications and capacities of permanent storage sites. Considering these aspects, we classify the problem as a network design problem. The problem is modeled as mixed-inter linear program to minimize the supply chain's net present value for a given planning horizon. In doing so, the annual investment and operating costs of the network are regulated with the goal of achieving a preset emission capture target. The model is solved via CPLEX for a case study of emission sources in northern Germany and possible storage locations under the seabed of the North Sea. Preliminary results are presented and analyzed in terms of network participating costs, shared transportation infrastructure due to mode choice and transport condition, as well as storage costs. The results can serve as an indicator for policy and industry stakeholders to consider CCS in their greenhouse gas reduction plans.

■ TA-07

Thursday, 8:30-10:00 - ESA J

Decision Support for Sustainable Production Systems and Supply Chains

Stream: Decision Analysis and Support
Invited session
Chair: *Christian Thies*

1 - Decarbonizing primary steelmaking: Strategic capacity modification and reduction planning
Yannik Graupner, Fabio Rausch, Christian Weckenborg, Thomas Spengler

Due to climate change, high-emission industries need to transform their production processes toward low-carbon technologies. Therefore, steelmakers are planning to close and replace currently operated production facilities long-term. However, production facilities of the conventional blast furnace-basic oxygen furnace route can also be modified to achieve emission reductions in the medium term. Against this background, we present a planning model to support decisions about closing or modifying production facilities within production networks for conventional primary steelmaking. Within the literature on strategic capacity planning in manufacturing, our approach for the first time includes time-dependent emissions budgets that initiate the transformation process. Also, plant modifications to reduce specific greenhouse gas emissions are included. The mixed-integer linear programming model aims to maximize the net present value of steelmaking, considering revenues from sales and costs for production and transportation. Using different climate scenarios, the dynamic transformation of a European steelmakers' production network is examined in a case study. The results indicate that modifying production facilities before closing them is more favorable in the case of site-specific emissions budgets than emissions budgets for the entire network.

2 - Economic assessment of electric energy storages in production systems

Matthias Gerhard Wichmann

Energy systems in manufacturing companies are transforming into more sustainable ones. Driven by rising energy prices, companies are changing in three facets. First, energy consumption is reduced by modern production technologies and energy-oriented planning approaches. Second, energy, especially electrical energy, is generated renewably on-site and decentrally. Third, energy storages are set up to decouple energy acquisition and consumption. The resulting energy systems are dynamic economic systems that enable complex market interactions. Surplus energy is sold or stored; missing energy is bought from an energy market. The market is characterized by fluctuating prices. Previous research shows remarkable economic potential in the use and implementation of energy storages resulting from energy trading. However, the regulation of energy systems does not allow for an arbitrary use of energy storages. Storages must be part of either the energy production or energy consumption system, which limits its technological and economic potential. Currently, there is a lack of approaches that allow for a regulation-adequate economic evaluation of energy storages in production systems. In this contribution, an energy-oriented Lot-sizing and Scheduling approach is extended to include energy economic decisions that take into account regulations on the use of energy storages. In addition, the cost and energy savings potential of energy storages is analyzed using a numerical case study. The study reveals the economic and energy saving potential in comparison to a state-of-the-art as well as to regulation-free energy-oriented Lot-Sizing and Scheduling approaches. The results are a basis for evaluating investments in companies as well as the consequences of regulations in the energy market.

3 - Optimal design of socially sustainable supply chains through activity analysis and social life cycle assessment

Lea Franze, *Karsten Kieckhäfer*

Driven by due diligence requirements, compliance with social standards is becoming increasingly important in the design of global supply chains. However, due to the often qualitative and subjective nature of the data, social sustainability is rarely examined in the current supply chain design research or often approached in an oversimplified manner.

We address this gap by developing a novel network planning approach that incorporates social life cycle assessment, activity analysis, and mixed-integer linear programming. Based on social life cycle assessment, social impacts at each level of a supply chain are computed as medium risk hours associated with a specific process at a specific geographic location. Activity vectors, representing the relevant inputs and outputs of each process from a techno-economic and social perspective, are then derived. The optimization model determines the activity level of each activity, i.e., whether and to what extent a process is used at a specific location. The activity levels are constrained by capacity limits of the locations, which can be adjusted by deciding on capacity expansions. While we consider a cost minimizing economic objective function, the acceptable level of social risk is limited to maximum values for medium risk hours.

The approach is applied to raw material extraction and processing in the supply chain of lithium-ion batteries for electric vehicles. The analyses show trade-offs between costs and social impacts, particularly in cobalt mining, where investments in additional mining capacity in Australia and Canada can reduce the social risks associated with cobalt from the Democratic Republic of Congo.

4 - Green Hydrogen Supply Chain Network Design for Aviation: Model Development and Case Study for German Airports in 2050

Akin Ögrük, *Rebecca Marx*, *Christian Thies*, *Sebastian Stiller*

Hydrogen-based propulsion concepts for aircraft are considered a promising technology towards the decarbonization of aviation. While the development of respective aircraft models is still in progress, questions regarding the supply network of green hydrogen are arising. We present a formulation of the hydrogen supply chain network design problem that focuses on the aviation sector. The mixed-integer linear programming model minimizes the total cost of hydrogen supply by deciding on locations, capacities, transportation modes and hydrogen flows. The respective supply chain starts with the generation of renewable electricity, which is used for the electrolysis of water. The gaseous hydrogen obtained from this process needs to be liquefied (by cooling it down to below -253 'C) before it can be used to refuel the aircraft. Moreover, various transportation and storage processes for gaseous and liquid hydrogen are involved between the electrolyzers and the airports. Our model formulation considers the spatially dispersed availability of renewable electricity, the techno-economic characteristics of hydrogen production, liquefaction and transportation (e.g., pronounced economies of scale), as well as the specific requirements of hydrogen handling (e.g., losses during transportation and storage). The application is illustrated for the case of Germany in 2050, considering the hydrogen pipeline backbone projection. Optimal network designs for different demand scenarios are also analyzed and results are presented.

■ TA-08

Thursday, 8:30-10:00 - ESA M

Manufacturing

Stream: Supply Chain Management
Invited session

Chair: *Margaretha Gansterer*

1 - A branch-and-price algorithm for scheduling continuous steel annealing lines

Sebastian Wegel

Continuous annealing is a core process in steel cold-rolling facilities, where order-specific pieces of flat steel, wound up to coils, are processed through an annealing furnace to achieve defined material properties. To enable a continuous process, the coils are welded together before entering the line. Whenever two consecutive coils are incompatible, a special dummy coil called stringer is used to connect them, which reduces efficiency and adds costs and emissions. We consider the scheduling of coils with specific due dates and alternative order-specific processing modes on parallel heterogeneous lines. The problem is to simultaneously assign coils to lines and sequence them on these lines with a defined processing mode with adherence to tardiness constraints while minimizing the number of stringers needed. To address this problem, we formulate it as a mixed-integer linear problem. To solve it, we propose a branch-and-price algorithm approach based on a Dantzig-Wolfe decomposition by annealing lines. The approach is implemented using the SCIP framework. We present the underlying problem decomposition, implementation, and some first numerical results.

2 - A Genetic Algorithm with LSTM-Based Fitness Function for Integrated Procurement and Scheduling Optimization in Hybrid Flow Shop Systems with Uncertainty

Benjamin Rolf, *Alexander Beier*, *Tobias Reggelin*, *Heiner Stuckenschmidt*

We present an integrated approach to address the hybrid flow shop scheduling problem (HFSP) and the order allocation problem (OAP) simultaneously. Our objective is to generate synchronized procurement-scheduling decisions that minimize combined procurement and job tardiness costs. Our hybrid method employs a genetic algorithm with an LSTM-based supervised learning model as a replacement for the computationally expensive fitness function.

While much of the existing literature focuses on abstract, long-term decision problems, our model provides daily operational decision support using a real-world case study from the printed circuit board assembly industry. With its flexible formulation of the HFSP and the OAP, our approach can be applied to a wide range of industrial settings with minimal adjustment effort.

As an operational support system, our method must account for the effects of past decisions, such as pending orders, partially processed jobs, and occupied machines. We evaluate our approach using a rolling horizon approach, which provides a more realistic performance evaluation than the fixed horizon setting commonly used in the literature. This approach also enables us to incorporate stochastic events such as new job arrivals, lead time shifts, and machine failures.

We evaluate our method on instances of two sizes (small and large), two horizon types (fixed and rolling), and 72 cost scenarios. Our results demonstrate that our method performs close to optimally on small instances. On large instances, in the absence of an existing baseline for comparison, we compare our method to an approach that solves the HFSP and OAP sequentially and show that our integrated method achieves significant cost savings.

3 - Developing a relax-and-fix matheuristic for the multi-level aggregated production planning of modular products

Philipp Stylos-Duesmann, Thomas Volling

Automotive supply networks are characterized by multi-tiered structures of specialized suppliers that sequentially integrate standardized modules into a large number of end product variants. Coordinated planning is critical within the network to effectively respond to increasingly occurring supply bottlenecks and shifting customer demand. We develop an integrated approach for the coordinating aggregated production planning problem considering multi-level supply networks, complex product structures and the flexibility to adjust capacity. We formulate the problem as a MILP and present a relax-and-fix matheuristic combining process-based and time-based decomposition. The proposed approach is evaluated on synthetic data sets of practically relevant complexity, which resemble the operating conditions of a real automotive supply network. Our results demonstrate the effectiveness of the proposed approach and its flexibility to adopt to varying levels of detail and complexity of the supply network. We conclude that it offers promising potential to provide decision support in a wide range of practical supply chain planning settings.

4 - Decentralized Collaborative Job Reassignments in Additive Manufacturing

Margaretha Gansterer, Dominik Zehetner

Cloud Manufacturing (CMfg) systems are considered to be powerful tools for decreasing costs while increasing supply chains' flexibility by applying the paradigm of the sharing economy. Especially in combination with Additive Manufacturing (AM), CMfg is seen as a key enabler of collaborative production systems. Although collaborative production planning is proven to decrease the costs of AM operations, there is still a lack of planning models that reduce entry barriers for collaborative systems. Therefore, we propose a decentralized collaborative production planning framework for AM. In our approach, machines autonomously select jobs from the existing production plan in order to forward them to other suppliers that can produce these parts more efficiently. A CMfg platform establishes job forwarding and creates promising bundles of digitally transferred parts. Manufacturing machines then autonomously bid on the packages via a combinatorial 2nd price reverse auction. Costs of the reallocated bundles are shared throughout a Shapley value-based approach without reporting critical information of the agents. In our computational experiments, we benchmark our proposed framework to a centralized planning approach. We observe that our framework reaches the effectiveness level of the benchmark solution. In terms of computational time, we demonstrate that the auction-based framework strongly outperforms the benchmark algorithm. We also show that the mechanism leads to individual rationality and that agents particularly benefit if they both offer and acquire production jobs through the auction.

■ TA-09

Thursday, 8:30-10:00 - ESA O(st) 221

Optimization with nonsmooth or combinatorial structures

Stream: Continuous and Global Optimization
Invited session
Chair: *Alberto De Marchi*
Chair: *Matthias Gerdts*

1 - Convergence of Successive Linear Programming Algorithms for Noisy Functions

Christoph Hansknecht

Gradient-based methods have been highly successful for solving a variety of both unconstrained and constrained nonlinear optimization problems. In real-world applications, such as optimal control or machine learning, the necessary function and derivative information may be corrupted by noise, however. Sun and Nocedal have recently proposed a remedy for smooth unconstrained problems by means of a stabilization of the acceptance criterion for computed iterates, which leads to convergence of the iterates of a trust-region method to a region of criticality.

We extend their analysis to a successive linear programming algorithm introduced by Byrd et al for unconstrained optimization problems with objectives that can be characterized as the composition of a polyhedral function with a smooth function, where the latter and its gradient may be corrupted by noise. This gives the flexibility to cover, for example, (sub)problems arising image reconstruction or constrained optimization algorithms.

We provide computational examples that illustrate the findings and point to possible strategies for practical determination of the stabilization parameter that balances the size of the critical region with a relaxation of the acceptance criterion (or descent property) of the algorithm.

2 - Bilevel Optimisation for Selecting Hyperparameters for Nonlinear Support Vector Machines

Samuel Ward, Alain Zemkoho

Nonlinear support vector machines are a staple of classification. They require the user to tune specific parameters such as the regularisation term and choice of kernel. Traditionally, this tuning has been approximated using cross validation and a grid search. But this method scales very poorly with the number of hyperparameters. In this research presentation, we will introduce bilevel optimisation and use this framework to model the hyperparameter turning problem. From here, we introduce stationarity concepts and constraint qualifications for bilevel programs. We will conclude with our solution method and numerical experiments.

3 - Multi-Target Dynamic Scheduling of Multiple Agents Involving an Advanced Piecewise Linearization Technique of Value Functions

Viktoriya Nikitina

A growing number of autonomous agents (mobile robots, ground and aerial vehicles) makes their efficient and safe operation a major challenge to address. Typical problems, which can be treated by the approach presented here, can be described as follows. Given multiple autonomous agents, several a priori known moving obstacles and different static target regions, the agents are supposed to reach the targets while avoiding the obstacles. The overall goal is to create an optimal schedule (i.e. to determine the starting time of each agent), to assign all agents to the targets and to compute their optimal paths.

The whole setting has a bilevel structure and can be mathematically described by a mixed-integer nonlinear problem. While the upper level optimization problem deals with the scheduling of all agents, the lower level one provides the shortest path for each of them. The latter problem is solved exploiting a discrete value function approach based on the Hamilton-Jacobi-Bellman equation from dynamic programming. The original optimization problem can be thus reformulated as a nonlinear single-level one. It is then linearized using a sophisticated piecewise-linearization technique and numerically solved by a robust and fast mixed-integer linear solver.

■ TA-10

Thursday, 8:30-10:00 - ESA W(est) 221

GOR Master Thesis Awards

Stream: PC Stream
Award Competition session
Chair: *Kevin Tierney*

1 - The Dial-a-Ride Problem in Theory and Practice: Analysing Applications as a Complement to Public Transit

Lorenz Saathoff

The concept of demand-responsive transport is seen as a promising solution for the necessary changes in the mobility sector in the context of sustainable urban transport. This work examines and compares the needs of dial-a-ride services (DARS) in practice and the problems considered in the scientific world, introducing a classification scheme for real-life services. A research gap is identified regarding the consideration of services that are integrated into the public transport network, while DARS can play a crucial role in improving transport services in terms of punctuality, frequency, and flexibility. Based on these [U+E085]ndings, a model for the dial-a-ride problem with public transport integration is presented. The model aims to minimise the

sum of waiting times for all passengers, focusing on suburban stations with realistic route data. The model is optimally solvable for small instances, but a heuristic approach based on simulated annealing is proposed for larger instances. The heuristic produces good results quickly. The research results suggest that the model is well suited to address the problem discussed and is transferable to real-world scenarios. The heuristic approach provides reliable results in a reasonable computational time and is therefore more suitable for practical applications.

2 - On the k Shortest Simple Paths Problem Using Biobjective Search
Max Huneshagen

The k simple shortest paths problem (kSSP) for a simple weighted digraph is a classic combinatorial problem. Although Yen's algorithm no longer possesses the best known time complexity, it remains an important practical benchmark for kSSP algorithms. Roditty and Zwick developed a method that computes the k shortest simple paths by searching for a second shortest path 2k times without giving an explicit algorithm to solve this task. We close this gap by providing a new easily implementable algorithm based on a novel biobjective search approach that efficiently determines the second shortest path with respect to a given shortest path. As a result, we obtain a new fast and applicable kSSP algorithm whose time complexity matches that of Yen's algorithm. Moreover, we discuss the framework of the asymptotically fastest kSSP algorithm due to Gotthilf and Lewenstein and use it in connection with a recent breakthrough result on the all pairs shortest paths problem by Orlin and V ´egh to show the existence of an O(kmn) algorithm for kSSP for integer costs. This improved time complexity bound is the best known for this relevant special case. Computational experiments show that our new algorithm is significantly faster on road and grid graphs.

3 - Lower Bounds for Simplex Pivot Rules via Markov Decision Processes
Nils Mosis

It is a major open problem in the fields of operations research and linear optimization whether there is an efficient pivot rule for Dantzig's simplex algorithm. We show that it is not possible to obtain the desired strongly polynomial running time with a pivot rule that can be written as a combination of Bland's pivot rule, Dantzig's pivot rule, and the Largest Increase pivot rule - three of the most classical simplex pivot rules. The proof is based on a close relation to the policy iteration algorithm for Markov decision processes. More precisely, we construct a family of Markov decision processes for which policy iteration performs the same exponential sequence of improving switches when applied with any of the three pivot rules. This behavior yields that the worst-case running time of the algorithm is exponential for every combination of the considered rules. Finally, due to the connection between both algorithms, we obtain the same exponential lower bound result for the simplex method.

■ TA-11

Thursday, 8:30-10:00 - ESA H

Industrial energy systems

Stream: Energy and Environment
Invited session
Chair: *Hannes Hobbie*

1 - Gotta catch 'em all: Modeling All Discrete Alternatives for Industrial Energy System Transitions
Hendrik Schricker, Benedikt Schuler, Christiane Reinert, Niklas von der Aßen

Industrial decision-makers often base decisions on mathematical optimization models to achieve cost-efficient design solutions in energy transitions. However, since a model can only represent a simplified reality, the optimal solution of an optimization model does not necessarily identify the best real-world energy system. Exploring near-optimal design spaces, e.g., by the Modeling to Generate Alternatives (MGA) or the Modeling All Alternatives (MAA) method, provides a more holistic view of decision alternatives beyond the cost-optimal solution. However, while the MGA method suffers from uneven coverage of the near-optimal solution space, the MAA method misses out on discrete investment decisions. Incorporating such discrete investment decisions is crucial when modeling industrial energy systems. Our work extends the MAA method by integrating discrete design decisions. We design an industrial energy system transition using a mixed-integer linear program. First, we explore the continuous, near-optimal design space by applying the MAA method. Subsequently, we sample all discrete design alternatives from the continuous, near-optimal design space. In a case study, we apply the extended MAA method to investigate all near-optimal transitions of an industrial multi-energy system. We identify 128 near-optimal design alternatives where costs are allowed to increase to a maximum of one percent offering decision-makers more flexibility in their investment decisions. Furthermore, we find that the integration of renewables is a necessary condition for cost-efficiency in all near-optimal alternatives. Our work enables the analysis of discrete design alternatives for industrial energy transitions and supports the decision-making process for investments in energy infrastructure.

2 - Optimization of Sustainable Cloud Infrastructure Networks Considering a Utilization of Excess Heat
Lydia Hilarius, Tristan Becker

The exponential increase of cloud workloads and strong growth of the data center market is leading to a significant rise in power consumption and associated CO2 emissions. At the same time, the heating sector is a major contributor to global energy-related CO2 emissions. Since data centers convert almost all of the electricity they consume into heat, linking the two sectors offers tremendous opportunities for decarbonization. However, the use of excess heat remains rare in practice. To realize this potential, it is essential to analyze the integration of heat utilization into cloud infrastructure. Hence, we propose an optimization framework for the network design of cloud infrastructures that incorporates the option of excess heat utilization and accounts for further sustainability drivers such as energy efficiency, renewable energy sources, and cooling technology choices. Strategic decisions include multi-period location decisions for cloud infrastructure, wind and solar generation capacity, and infrastructure for heat utilization. Operational decisions include the provision of computing capacity, energy supply, and heat utilization on a seasonal scale. Our European case study demonstrates the potential of this approach to achieve significant reductions in carbon footprint and cost. Furthermore, we provide valuable insights for industry and policymakers.

3 - Identifying critical components for energy system resilience with structural indicators: case of cyber-attack
Madhura Yeligeti, Hans Christian Gils, Patrick Jochem

The design of future energy systems must account for resilience to sudden and extreme events, both natural and human-induced. Events like cyber-attacks, are especially difficult to predict and depending on their extent, can paralyse energy systems of entire countries. Hence, resilience measures for future energy systems require suitable indicators for identifying vulnerable elements during system design and analysis. Energy system optimization models apply various socio-economic scenarios to design and analyse future energy systems. To assess system resilience, various extreme events can be incorporated as stress cases in the models. But, system response depends significantly on time, duration, location and spatial extent of the event. Hence, for investigating improbable cases like cyber-attacks, a myriad of parameter combinations should be tested in the energy system model . This makes the analysis highly time consuming for complex energy system models. Therefore, we work with a test energy system with limited technological, spatial and temporal scope. Thousands of stress cases can be simulated on the simplified model and respective system performances can be evaluated. Structural indicators like technological diversity in operation, energy demand etc. are used to characterize system components. The aim of this study is to identify key indicators and their combinations that are especially critical to system resilience. Machine Learning regression is used to establish a correlation between these indicators and their respective stress-response. Extending the indicators to more complex and realistic energy system configurations will help in identifying a system's most critical components for efficient application of preventative measures for system resilience.

■ TA-12

Thursday, 8:30-10:00 - ESA K

Control Mechanisms and Agent Behaviour in Energy Markets

Stream: Energy and Environment
Invited session
Chair: *Hannes Hobbie*
Chair: *Kathrin Fischer*

1 - Congestion avoidance in power grids - An approach based on flexibility premiums

Tizian Schug, Jannis Eichenberg

Congestion management is an important aspect when studying electrical power grids, especially when considering the increase of volatility and unpredictability of supply caused by renewable energy sources. Demand side flexibilities can be used to mitigate congestions. However, providers of such flexibilities do not have an intrinsic motivation to make their potential available for congestion management, instead they aim to use their flexibility to buy electricity at the cheapest times. Transmission system operators (TSO) interested in using flexibility options thus need to create incentives such as paying a premium. In this work, we investigate different designs of flexibility premiums and compare their impact on congestion management with outcomes of a scenario in which the TSO has full control of flexible devices.We define a bi-level optimization approach in which we solve the congestion management problem while simultaneously clearing the market and dispatching flexible technologies. The first level represents the TSO's decisions to manage congestions at the lowest possible cost. Management options consist of increasing/decreasing power plant outputs and setting a flexibility premium. At the lower level, the premium influences the dispatch of the flexible technologies, which in turn influences the market clearing. First results show that specific premiums are more suitable than non-specific ones. Giving direct control of flexible technologies to the TSO yields the most favorable outcome in terms of congestion management and system costs.

2 - The Energy Aggregator Problem - A Holistic MILP Approach

Kai Hoth, Béla Wiegel, Kathrin Fischer

Future energy systems require efficient management of decentralized and renewable energy resources (DERs). Energy Aggregators (EAs) provide a promising solution for managing these resources by aggregating DERs of multiple prosumers. The EA problem involves scheduling different types of DERs with specific technical restrictions and trading energy on external markets as well as internally between prosumers of the same EA.

In this work, we propose a MILP approach to solve the holistic EA problem. The approach considers the technical restrictions of DERs in detail and integrates power-to-heat-systems with heat pumps and heat storages considering the inherent thermodynamic relations. The model includes external trading options on wholesale level and on local market level, which enables its application in different system concepts and allows to pursue economic as well as sustainability goals. By considering specific restrictions of different DER types, the proposed model can accurately represent the behavior and interaction of DERs in the system, allowing for precise scheduling and trading decisions. To test the model, we apply it to a case study of one EA with 111 aggregated households and different DERs such as power-to heat systems with heat pumps, electric vehicles, battery storages, time-shiftable loads, and photovoltaic systems. The presented results of the case study verify the functionality of the EA model and reveal the synergetic potential of EAs by aggregating different types of DERs.

3 - Robust integer programming for a future 100% renewable energy supply system - an exploratory study

Felix Engelhardt, Christina Büsing, Heidi Heinrichs, Sebastian Kebrich

Any future greenhouse gas neutral energy system will largely depend upon variable renewable energy sources (VRES). However, their production levels are inherently fluctuating, as they depend upon the weather. Here, weather patterns impact not only location choices for VRES, but also the capacities of energy storage required to account for these variations. Frequently, this is dealt with by picking a reference year to be used for scenarios of energy system design and operation. There exists extensive research on designing fully RES-based energy systems, using the open-source FINE model framework and including cross-country hydrogen supply networks. It has also been shown that the results are dependent upon the choice of the reference year. To evaluate the problem of picking a reference year, a study by Caglayan et al. uses the weather data of 38 years and outlines the differences for the resulting energy system. In a follow-up study, they used an iterative minimal cost-optimization approach to generate a cost-effective solution in terms of total annual cost (TAC) that remains feasible across all years. The FINE framework is based in mixed-integer linear programming and thus allows for a direct integration of robust optimization methods into the framework. In this work, we evaluate the extent to which this is solvable computationally when applying robust optimization based on uncertainty on the power generation, i.e. the power produced as a function of the weather scenario, the current time-step, the location and the capacity of installed production units. Furthermore, we evaluate the effects of a trade-off between modelling granularity and robustness in planning on the feasibility and TAC of energy systems if the latter are evaluated without time-series aggregation.

4 - Design solutions for regional flexibility markets with strategically acting aggregators

Hannes Hobbie, Ramteen Sioshansi, Dominik Möst

Future decentralised energy systems with an increasing degree of mobility and heating sector electrification require novel solutions for managing congestion in electricity grids. This includes new forms of coordination between grid operators and flexibility providers. So-called regional flexibility markets are likely to play an essential role in the market-based coordination of flexibility provision between grid operators and flexibility suppliers.

In addition to the technical challenges, aspects related to market design and the behaviour of individual stakeholders have a significant impact on possible design solutions. Compared to the traditional congestion management practices used in Germany, so-called regional flexibility markets might suffer from low liquidity, leading to market inefficiencies.

In this work, we apply methods from equilibrium and complementarity programming to study the market interactions of strategically acting aggregators under different pricing schemes for flexible demand-side products in regional flexibility markets. The expected results will show how combined day-ahead and congestion management pricing schemes can mitigate the market power of demand-side aggregators.

■ TA-13

Thursday, 8:30-10:00 - ESA W(est) 121

Shunting

Stream: Mobility and Traffic
Invited session
Chair: *Han Hoogeveen*

1 - Reducing the number of shunt movements.

Rens de Heer, Roel van den Broek, Han Hoogeveen

The Train Unit Shunting Problem with Service Scheduling (TUSP-wSS) is the problem of constructing a conflict free schedule for a shunting yard that facilitates the parking and servicing of (passenger) trains. Van den Broek et al. have shown that meta-heuristics are successful in solving these problems. Human planners have noticed, however, that solutions given by these algorithms may have an unusually high number of movements. We propose an algorithm that serves as a post-processing step by rescheduling the movements of one or two trains in a minimum number of movements. Our algorithm first determines the potential parking intervals and spaces on the yard. Next, it computes an optimal route for the train as a shortest path in a network, where the potential parking intervals and spaces correspond to the nodes; the required service tasks are also included into this path. Computing the optimal pair of routes for two trains is done using techniques from multi-agent pathfinding. The algorithm enumerates pairs of routes with a minimal sum of movements and uses constraint programming to compute the starting time for each movement. Using this algorithm, we can change the matching between incoming and outgoing trains of the same type and reschedule each train to their new departure. In addition to decreasing the number of movements, this algorithm can also be used to improve near-feasible plans by rescheduling conflicting trains.

2 - Scheduling mechanics on a Shunting Yard: skills, synchronization, and train movements

Han Hoogeveen, Kees Szabo, Roel van den Broek

When trains are not in use, they reside on shunting yards. On these shunting yards, the trains move around following a predetermined shunting plan to ensure an efficient use of the shunting yards. The trains have to be checked and small repairs have to be carried out by mechanics working at the shunting yard. Obviously, tasks cannot be carried out when a train is moving. Therefore, trains can have multiple moments at different times and locations where they are stationary and a mechanic is allowed to work on them. As some tasks require certain skills, there are restrictions on which mechanics can do which tasks. Some of these tasks require two mechanics to work on at the same time, and therefore the time when these mechanics start working on this job has to be synchronized. At the moment, scheduling is done ad hoc by the mechanics at the start of their shifts. The manual planning takes time out of a possibly busy schedule while not always resulting in a desirable, robust solution. Therefore, in this thesis, we propose a local search approach for scheduling mechanics on a shunting yard subject to these constraints. We aim to create robust schedules for the mechanics which can be generated before their shifts start and are easy to update if a disruption in the shunting plan were to occur. Our method is able to generate good results on a variety of realistic problem instances.

3 - A two-layered lagrangian relaxation approach to coordinate macroscopic and microscopic train movements at busy high-speed railway stations

Richard Lusby, Qin Zhang, Pan Shang, Chang Liu, Wenqian Liu

Railway stations are highly important junctions in high-speed railway networks. Compared to the railway track infrastructure between stations, they offer many more routing possibilities for scheduled train movements. In this paper, we study the problem of routing and platforming trains at busy, complex high-speed railway stations. We design a two-layered space-time network to capture macroscopic and microscopic perspectives, model the combined problem as a large integer linear program, and propose a Lagrangian Relaxation approach to solve the routing and platforming problem. The suggested decomposition induces train independent path problems at the macroscopic level and guides the choice of paths through the inclusion of Lagrangian multipliers that provide information on microscopic level infrastructure utilization. We test the proposed methodology on real-life instances from the busiest high-speed line in China, compare its performance against various other decomposition strategies, and report encouraging results.

4 - Algorithmic Rail Depot Planning

Gian Tuor, Harold Tiemessen, Fabian Leuthold, Bruno Pfeiffer

The operational depot planning process is a crucial aspect of railway passenger operations that is highly dependent on prior planning processes, such as rolling stock planning and timetabling, and is particularly sensitive to short-time changes and disruptions. As a result, this task is typically performed as late as possible, leading to high time pressure for dispatchers. Furthermore, efficient depot planning will become even more critical in the future as passenger rail traffic and rolling stock numbers increase, particularly as available land for depot expansion near stations becomes scarcer. In this study, we study the Track Assignment Problem (TAP), which aims to assign train units to tracks based on the topology of the depot and the arrival and departure times of all train units. The objective is to develop a feasible depot plan that minimizes a user-defined cost function. To achieve a feasible track assignment, departing train units may not be blocked by parked train units, and restrictions on parking permission must be considered, including the capacity of each shunt track. Existing literature has addressed TAPs by formulating them as Set Partitioning Problems and employing column generation to tackle the exponential number of decision variables. In contrast, we propose a MIP formulation that has a quadratic number of decision variables. We solve the MIP models using Google OR Tools. Numerical experiments on real-life test cases show that our MIP approach performs very well and provide insightful information on depot utilization, which might be useful for (re-) designing shunting areas.

■ TA-14

Thursday, 8:30-10:00 - ESA W(est) 120

Routing problems and traffic assignment

Stream: Mobility and Traffic
Invited session
Chair: *Paul Rieger*

1 - Solving the Capacitated Arc Routing Problem with LocalSolver in an industrial context

Bienvenu Bambi

A LocalSolver customer in charge of maintaining public assets needs to go through the entire road network within a defined area, minimizing the total travel time and considering various constraints such as traffic direction and speed limits, and ensuring that each road segment is processed only once. The problem is formulated as a Capacitated Arc Routing Problem (CARP), a well-known NP-hard problem, which offers a suitable modeling approach to address the unique challenges of this specific case using LocalSolver. To model the given scenario, we represent the area to be surveyed as a directed graph, where arcs correspond to road segments (accounting for traffic direction), and vertices represent intersections between roads. In this specific project, there is no capacity constraint to consider, allowing us to focus on other problem aspects. The CARP is applied to determine an optimal route tour that satisfies all requirements while minimizing travel time and operational costs. The talk will present a solution to this problem based on local search, one of LocalSolver competitive edge technologies. Modelling choices as well as other specific business rules and results on large size instances will also be shown.

2 - Time-Dependent Shortest Path with Travel Time Equivalents of Inconveniences

Marc Gennat, Lukas Spengler

In order to predict modal shifts of future mobility systems, it is crucial to make different modes of transport comparable. Inconveniences of a trip can be modeled by adding travel time equivalents to the actual travel time of an origin-destination-relation (Intraplan Consult, Standardisierte Bewertung). This sum is called travel resistance. Examples of inconveniences are changing trains, waiting or walking times to stations, and analogue searching for parking spaces with motorized private transport. This contribution adapts well-known shortest path algorithms, e.g. Dijkstra or ALT-Algorithm, which compute the minimum travel distance or travel time, to find the path with minimum travel resistance for different modes of transport. The initial weight of an edge in the directed and time-dependent graph is defined by a vector representing departure times. In addition, the edges and nodes of the graph contain information about the mode of transport, vehicle affiliation or parking space availability. The developed algorithm detects inconveniences and adds them to the edge weight, which is not only travel time, but travel resistance. In this contribution the algorithm takes into account different start times and weekdays of the journey, which change the travel resistance, and is described in detail with flowcharts. In further research, the minimum travel resistance of a relation for each mode of transport can be transferred to the modal split using empirically determined parameters (Intraplan Consult). The graph can now be adjusted or extended, for example to add bus routes, remove parking spaces or increase departing frequency. Applied to all ways of a city, the modal shift of future public transport scenarios can be predicted.

3 - Development of a Centrally Managed Dynamic Traffic Assignment Algorithm Considering Route Choice Effects on Capacity

Paul Rieger, Arturo Crespo Materna, Andreas Oetting

The increasing volume of personal motorized vehicles (PMVs) in cities has become a serious issue leading to congestion, noise and air pollution as well as high land use consumption by parking vehicles. To encounter these issues and in the context of a centrally managed on-demand ride-pooling service that is operated by a fully automated and connected vehicle fleet we suggest a Capacity Traffic Management System (CTMS) which includes the task of scheduling incoming orders in real time. Hereby, the global management of routing decisions and complete information about traffic flows through floating car data offers the possibility to find a more efficient solution for routing decisions compared to more suboptimal solutions generated by independent, non-cooperative user choices.

The central challenge for the routing algorithm is imposed by the dynamic network loading problem in which the future demand is not exactly known in advance. The suggested algorithm takes into account incoming transportation requests and suggests optimal route and departure time choices considering the estimated future demand aiming to reach a balanced capacity utilization throughout the network. As part of the scheduling, reliable driving time estimations are added based on traffic simulation.

4 - Dynamic Snow Plowing
Karl Doerner, Georg Erwin Adrian Fröhlich, Margaretha Gansterer

In snow plowing most studies focus on deterministic settings with little urgency yet enough time to plan. In contrast, we assume a severe snow- storm with little known data and little time to plan. We introduce a novel time-dependent multi-visit dynamic snow plowing problem and formulate it on a rolling-horizon-basis. To solve this problem, we develop an adap- tive large neighborhood search as the underlying method and validate its efficacy on team orienteering arc routing problem benchmark instances. We create real-world-based instances for the city of Vienna and exam- ine the effect of (i) different snowstorm movements, (ii) having perfect information, and (iii) updating intervals and look-aheads for the rolling horizon method. Our findings show that different snowstorm movements have no significant effect on the choice of rolling horizon settings. They also indicate that (i) larger updating intervals are beneficial, if prediction errors are low, and (ii) larger look-aheads are better suited for larger up- dating intervals and vice versa. However, we observe that less look-ahead is needed when prediction errors are low.

■ TA-15

Thursday, 8:30-10:00 - R 0077, VMP5

Scheduling in Health Care 1

Stream: Health Care Management
Invited session
Chair: *Sebastian Schiffels*

1 - A branch and price approach for integrated surgery and staff scheduling in operating theatres on a daily planning level
Stefanie Ebel, Jens Brunner, Thomas Koperna

Two of the most important, expensive and scarce resources in hospitals are physicians and operating rooms. Therefore, effective and efficient scheduling of these resources is among the most relevant planning tasks within hospitals. The decisions to be made on the daily planning level regard the sequencing of patients' surgeries and the assignment of appropriate staff to surgeries. Since there are several interdependencies between surgery schedules and physician rosters, it is a meaningful approach to consider both planning problems within one integrated optimization problem. We provide MIP models for a branch and price algorithm that combines both scheduling problems within one solution approach to create schedules for surgeries as well as for operating room staff. We evaluate our algorithm with respect to different aspects of flexibility in this context and use test data based on a real-world dataset to provide meaningful insights.

2 - Continuous Integrated Task Assignment and Personnel Scheduling
Gerriet Fuchs, Katja Schimmelpfeng

The shortage of qualified personnel is a well-known problem in the healthcare sector. This results in two major challenges for hospitals:

1. qualified staff as a scarce and expensive resource; and 2. staff satisfaction as an important objective of workforce planning.

This means that both financial and fairness aspects must be considered in planning. The underlying idea to address both challenges is to introduce more flexibility into the workforce planning problem. Therefore, we present a novel approach to a flexible integrated work scheduling and task assignment problem to create flexible individual work schedules based on given tasks. This individualized approach allows us to consider, among other things, personnel preferences, work rules, and the fairness of the generated work schedules. Task-based scheduling is a realistic problem in hospitals, where flexibility could be a viable tool to address the above challenges.

To analyze flexibility's potential, we create flexible and feasible work plans using a mixed-integer model that is not based on arbitrarily defined time periods during a day. Therefore, the complexity of the planning problem is independent of the time granularity of the problem. This allows for maximum flexibility in the planning process. This approach enables us to identify the benefits of introducing flexibility in a simple and concise way. This way, we lay the basis for further research and identify steps that can be taken to improve workforce planning without compromising quality of care.

3 - Supporting elective surgery scheduling under ICU capacity uncertainty
Arne Henning Witteborg, Michael Römer

Intensive care units (ICUs) play a crucial role in the clinical pathway of patients, and the capacity of a given ICU is not only limited by the number of beds, but also by the number of available intensive care nurses. On the other hand, the ICU occupancy is highly volatile since both the arrival of emergency cases and the patients' length of stay on the ICU are affected by uncertainty. As a consequence, scheduling elective surgeries that require post-operative ICU care is a planning problem under uncertainty that has to balance the objectives of minimizing the delays of elective interventions and maximizing the utilization of expensive ICU capacities with the risk of running out of ICU capacity. We model this problem as a stochastic optimization problem with a planning horizon of one week in which we approximate the uncertain and decision-dependent evolution of the ICU occupation using Monte-Carlo simulation. Specifically, our model aims at minimizing the delay of elective surgeries while representing the risk of exceeding critical occupancy levels as chance constraints. Our ICU occupancy model relies on standardized treatment and patient health state data for creating patient-specific length-of-stay distributions to reflect the reality of a broad range of patient types that are admitted on an ICU. We evaluate our approach using historical data from a real-world use case in a German hospital.

4 - Rehabilitation Therapy Scheduling with Teaming Requirements and Task Preferences
Sebastian Kling, Sebastian Schiffels, Jens Brunner

Physical therapy in acute care hospitals plays an important role in the rehabilitation of patients. Nevertheless, the profession must deal with staff shortages, and as a result the total number of treatments the hospital departments can offer is negatively affected. The therapist shortage is caused by a lack of qualified employees and absenteeism, which are results of high physical and mental workloads as well as a lack of employee retention strategies. Thus, the available staff must be scheduled in a way that is efficient and accounts for employee retention. Standard therapy cases require one therapist, while severe cases require two therapists at the same time. Here, one therapist needs to take charge of the treatment, while a second therapist fulfills a support function. This paper develops a multi-criteria optimization model for the daily rehabilitation therapy scheduling problem using a VRP formulation with time window and synchronization constraints. We integrate preferences fulfilment to help employee retention. While therapists can work on every patient in a lead or support function role, different preferences for the roles help to increase employee satisfaction, i.e., they improve adherence to retention objectives. We present a Branch-and-Price algorithm and show effects of different problem specific speed-up techniques. Also, we examine effects of task synchronization. We demonstrate the usage of the algorithm for realistic problem instances and show preliminary computational results.

■ TA-16

Thursday, 8:30-10:00 - R 0079, VMP5

Nonlinear and Global Optimization

Stream: Software for OR
Invited session
Chair: *Tristan Gally*

1 - Solving MINLPs to Global Optimality with FICO Xpress Global
Tristan Gally

This talk introduces FICO Xpress Global, which allows to solve general mixed-integer nonlinear problems to global optimality. We will discuss how existing features of the MILP and local NLP solvers are used and explain several different extensions for, e.g., spatial branching and convexification cuts, and their performance implications.

2 - Open-Source Software for the Global Optimization of Bilevel Programs and (Generalized) Semi-Infinite Programs
Daniel Jungen, Aron Zingler, Hatim Djelassi, Alexander Mitsos

Many decision-making problems in engineering are so-called hierarchical optimization problems which incorporate optimization problems embedded in their constraints. For example, flexibility analysis and optimization under uncertainty belong to this problem class.

A well-known solution approach to hierarchical optimization problems is the relaxation of the original problem through an adaptive discretization scheme whereby the discretization is adaptively refined to obtain increasingly tighter relaxations. Over the last two decades, multiple conceptually closely related solution algorithms using adaptive discretization schemes have been published. These publications typically compare computational performance on a benchmark test based on a collection of test problems. However, since the number of problems, the nature of the test problems, and the computational setups used often differ from one publication to another, a fair comparison is challenging. In addition, many of the existing algorithms use hyperparameters that affect computational performance, which further complicates a fair and meaningful comparison.

Our contribution to resolving these issues is threefold. First, we present an open-source C++ library containing multiple discretization-based hierarchical programming solvers for the global solution of bilevel and (generalized) semi-infinite programs. Second, we compile a benchmark library consisting of unified existing benchmark libraries and application-oriented test problems. Third, we conduct numerical performance tests using the large benchmark library to compare the implemented programming solvers to seek the 'best working' hyperparameters for each algorithm.

3 - TOPAS Model Fitting: A Tool for Parameter Identification of Dynamical Systems
Marek Wiesner, Kai Schäfer, Petr Shulpyakov, Christof Büskens

Parameter identification is crucial to simulate and optimize complex real-world processes. In many scenarios, such processes can be modeled as parameter-dependent ordinary differential equations (ODE). By adapting the parameters, the ODE model is fitted to measurements that are observed from real-world operations. There are many parameter identification methods, such as single shooting, full discretization, or gradient matching, each with advantages and disadvantages. A recipe for which method is best in a particular situation does not exist and experimentation with different approaches is necessary. Therefore, the choice of the solution method is an obstacle and requires expert knowledge.

Implementing multiple parameter identification methods is time-consuming and, especially for non-experts, error-prone. TOPAS Model Fitting solves both of these problems. It intuitively guides through the process of parameter identification. The tool uses algorithms for solving high-dimensional optimization problems and offers several easily configurable parameter identification methods. The user can conveniently test them and obtains direct visual feedback on whether the approach is successful.

In this talk, TOPAS Model Fitting will be presented. The focus will be on the implemented approaches for parameter identification. The limitations of the algorithms and their advantages and disadvantages will be discussed. We will see that no approach works well for every problem but that each algorithm performs well for different problems. These observations are based on running multiple experiments, originating from a comprehensive problem library. This flexibility of being able to conveniently test various solution approaches marks one of the benefits of TOPAS Model Fitting.

4 - Pooling adjacent violators under interval constraints
Kai Kopperschmidt

Approaches which "pool adjacent violators" are very simple and efficient methods to solve isotonic regression problems. We extend this type of algorithms to include non-uniform interval constraints in the complete order case. We prove correctness and linear computational complexity of a resulting approach. We also show that a straightforward implementation in C outperforms more general solvers on a sequence of specifically designed problem instances.

■ TA-17

Thursday, 8:30-10:00 - ESA O(st) 121

Routing Problems II

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Boris Grimm*

1 - Tighter LP-Relxations for the Railway Rolling Stock Rotation Problem with Vehicle Maintenance
Boris Grimm, Ralf Borndörfer, Julian Bushe

The Rolling Stock Rotation Problem (RSRP) is the task to group railway rolling stock to vehicles compositions and assign them to trips of a given railway timetable in an operational feasible and most cost efficient way. In real world applications several different rules have to be considered to claim solutions to the RSRP as operational feasible. An example for these type of constraints are distance based vehicle maintenance requirements which define a maximum mileage for individual vehicles between two stops at maintenance facilities. In Giacco et al. 2014 and Borndoerfer et al. 2016 MILP formulations were presented to solve the RSRP while considering maintenance requirements. In both applications a continuous flow to track the vehicle mileage is linked to a binary vehicle (hyper) flow to solve the problem. The LP-relaxations of both models suffer from a systematical error resulting from the Big-M like linking of the variables. In this talk we present a reformulation of the latter model using path variables to overcome this error. Due to the worst case exponential number of possible paths we present a dynamic way to generate promising candidates to solve the LP-Relaxation. The generation process is a shortest path computation in a two layered graph to decrease the computation time of the approach. We evaluate our approach on real world long distance train instances and compare the results to the ones found with the algorithm of Borndoerfer et al. 2016.

2 - Traffic Assignment and Network Design using Boscia.jl
Kartikey Sharma, Deborah Hendrych, Mathieu Besançon, Sebastian Pokutta

The Traffic Assignment (TA) problem forms a key part of many traffic flow and urban design processes. Efficient computation of the solution of this problem allows for the evaluation of larger and more complex traffic models and thus better city design. We extend the new Julia library Boscia.jl, which can solve convex integer programming problems using the Frank-Wolfe algorithm, to solve the TA and Network Design problem. We extend this library to take advantage of the special structure present in network problems and compare against the results from standard MILP formulations. We evaluate our method on traffic network data sets from the Transportation Networks library. Our results show the flexibility and high performance of this framework for solving such network problems.

3 - A Modified State Space of Ratliff and Rosenthal's Dynamic Program for the Joint Order Batching and Picker Routing Problem with Scattered Storage
Laura Korbacher, Stefan Irnich

Collecting ordered articles from different pick positions accounts for the lion's share of operating costs in warehouses and has great potential to reduce costs. Given a customer order, the single picker routing problem (SPRP) seeks a minimum-length picking tour collecting requested articles. Whereas with classic storage, each article is stored at a unique pick position, with scattered storage, an article can be stored at several pick positions. Consequently, the pick positions for the requested articles must be additionally selected. We consider the SPRP with scattered storage (SPRP-SS) and present a new modeling approach. We modify a recently published network-flow model with covering constraints based on an extension of the state space of the dynamic-programming formulation by Ratliff and Rosenthal. In this state space, the different possibilities of traversing an aisle are represented with arcs. Considering the SPRP-SS, the number of possible aisle traversals can increase significantly and lead to a considerably enlarged state space with parallel arcs. We modify the state space of Ratliff and Rosenthal and replace clusters of parallel arcs with small, sparse auxiliary networks to reduce the size of the state space. Besides

the SPRP-SS, we consider the joint order batching and picker routing problem with scattered storage. Here, instead of a single customer order, a set of orders is given. The problem is to group the given orders into capacity-feasible batches (one batch per picker) so that the total length of the resulting picker tours is minimized. We solve the problem with a branch-price-and-cut algorithm. The pricing problem is similar to the SPRP-SS and thus can be modeled accordingly to profit as well from the modified state space of Ratliff and Rosenthal.

4 - Resource-Window Reduction by Reduced Costs in Path-based Formulations for Routing and Scheduling Problems
Stefan Irnich, Timo Gschwind

Many routing and scheduling problems are modeled through variables that represent paths (routes, schedules, etc.). For such extensive formulations, branch-price-and-cut (BPC) algorithms constitute nowadays the leading exact solution technique and, most of the time, the pricing problem is a shortest-path problem with resource constraints that can be solved by a dynamic-programming labeling algorithm. For this setting, variable-fixing techniques based on the reduced costs of the paths have been proposed with the aim of eliminating arcs from the underlying network and speeding up the solution process of the pricing problem as well as of the overall BPC algorithm. For an efficient variable fixation, bidirectional labeling must be possible. We move one step forward and show how the reduced costs of paths can also be exploited to reduce the resource windows for many types of resources including the time resource and a load-related resource. This can be achieved without modifying the pricing problem network and altering the structure of the pricing problem itself. Moreover, different resources can be considered simultaneously. A straightforward reduction of the resource windows associated with the vertices of the network can tighten them, but this reduction does not translate into savings in computation times. On the contrary, the reduction of the resource windows is effective when distinct forward and backward resource windows are defined for each arc, and reduced independently based on the traversal direction of the arc itself. Moreover, an arc can be eliminated when one of its arc-specific resource windows becomes empty, and the explicit use of variable-fixing techniques can be avoided.

■ TA-18

Thursday, 8:30-10:00 - ESA O(st) 122

Optimization under Uncertainty

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Rebecca Marx*

1 - Optimization under Controllable Uncertainty
Rebecca Marx, Eva Ley, Maximilian Merkert, Tim Niemann, Sebastian Stiller

In several applications of optimization under uncertainty, one can reduce the uncertainty at a certain cost. In our model, the optimizer can accept additional cost for narrowing down intervals of uncertain parameters around an a-priori known value, possibly fixing the parameter to that value.

We refer to this new model as optimization under controllable uncertainty. We briefly contextualize our model with related uncertainty concepts from the literature, e.g., robust optimization and explorable uncertainty.

For several problems being solvable in polynomial time, we show that the linear optimization problem under controllable uncertainty can still be solved in polynomial time. In the talk, we focus on the three-stage problem of finding a shortest path between two nodes in a graph under controllable uncertainty.

2 - OWA Regret: A Novel Approach for Decision Making
Werner Baak, Marc Goerigk

In this talk, we introduce a novel approach for decision making called OWA Regret, which combines the well-known ordered weighted averaging (OWA) method with min-max regret. We demonstrate how this approach can be applied to discrete scenarios and show that it can be approximated using clustering algorithms. To evaluate the effectiveness of OWA Regret, we conduct two experiments: a selection problem with synthetic variables and a shortest path experiment based on real data from Chicago's street network. Our results show that OWA Regret provides a balanced trade-off between regret and OWA criteria. Specifically, we observe that OWA Regret is equivalent to Regret for very conservative weights and equivalent to OWA for very risk-neutral weights.

3 - Solving Wasserstein distributionally robust combinatorial optimization problems
Adam Kasperski, Pawel Zielinski, Marcel Jackiewicz

A class of combinatorial optimization problems with uncertain objective function costs is considered. The true probability distribution for the uncertain cost vector is unknown, but a sample of realizations of this vector, forming an empirical distribution, is available. The true probability distribution is assumed to lie with some prescribed confidence in a Wasserstein ball, centered on the empirical distribution. The goal is to find a solution minimizing the Conditional Value at Risk (CVaR) for the worst probability distribution within the Wasserstein ball. Some particular cases of this problem have recently been discussed in the literature. In this paper, the known results are extended and generalized to a wide class of combinatorial problems. The computational complexity of the problem is first characterized. Some exact and approximation methods of solving it are then proposed. These methods are based on solving a family of mixed integer programming problems. The results of some computational tests are presented.

■ TA-19

Thursday, 8:30-10:00 - ESA O(st) 123

Combinatorial Optimization II

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Emma Ahrens*

1 - Modification of the Ford-Fulkerson Algorithm for Temporally Repeated Flows or How can we engage as few workers as possible?
Emma Ahrens, Christina Büsing, Steffensen Sonja

In this talk, we analyze the optimization of logistical processes in hospitals and focus on the transportation of beds from the storage area to the hospital stations. The transportation problem is modeled using flow over time networks. We aim to find transportation plans which are easily executable by humans and obtain them by considering temporally repeated flows. Furthermore, they should be optimal with regard to other criteria such as having a minimal overall execution time (hence finding an optimal solution of the Quickest Transshipment Problem) or engaging as few employees as possible at every point in time.

Here, we show that the algorithm of Ford and Fulkerson for computing maximal temporally repeated flows can be modified to compute maximal temporally repeated flows where the maximal costs over all points in time are minimal. This allows us to find execution plans for the transportation of beds in hospitals, where the number of employees carrying beds is minimal at every point in time.

2 - Upper and lower bounds for the parametric minimum spanning tree one-interdiction problem
Nils Hausbrandt, Stefan Ruzika, Luca Schäfer

In this talk, we introduce the parametric minimum spanning tree one-interdiction problem. Given a graph whose edge weights depend linearly on a real-valued parameter from a parameter interval, the goal is to compute for every possible parameter value exactly one edge that when removed from the graph increases the weight of the minimum spanning tree as much as possible. Together with the parametric shortest path one-interdiction problem, this problem is the only parametric interdiction problem studied in the literature so far. The piecewise-linear and continuous function mapping the parameter to the weight of an optimal one-interdicted minimum spanning tree is called optimal interdiction value function. We present upper and lower bounds on the number of slope changes, called changepoints. Further, we relate them to the number of slope changes (breakpoints) of the optimal value function of the classical parametric minimum spanning tree problem, mapping the parameter to the weight of a minimum spanning tree.

3 - Maximizing a Submodular Function with Bounded Curvature under an Unknown Knapsack Constraint
Martin Knaack, Max Klimm

We study the problem of maximizing a monotone submodular function under an unknown knapsack constraint. A solution to this problem is a policy that decides which item to pack next based on the past packing history. The robustness factor of a policy is the worst case ratio of the solution obtained by following the policy and an optimal solution that knows the knapsack capacity. We develop an algorithm with a robustness factor that is decreasing in the curvature c of the submodular function. For the extreme cases c=0 corresponding to a modular objective, it matches a previously known and best possible robustness factor of 1/2. For the other extreme case of c=1 it yields a robustness factor of approximately 0.35 improving over the best previously known robustness factor of approximately 0.06.

4 - The submodular maximization problem with an unkown knapsack capacity
Sabine Muench, Sven de Vries, Stephen Raach

We study the problem of maximizing a monotone submodular function under an unknown knapsack constraint. An instance of this problem consists of a finite set of items, where each item is associated with a weight, and a monotone submodular set function defined on the set of items. The objective is to maximize the submodular function subject to an unknown weight constraint. We require that every single item fits into the knapsack. Our goal is to find an universal policy, that is, a fixed order of the items in which we pack the knapsack independent of the observations made while packing. If an item fits into the knapsack, the item is packed irrevocably. If the addition of an item exceeds the capacity of the knapsack, we stop packing the knapsack and output the solution.

It is well known that Wolsey's famous greedy algorithm (1982) solves the same problem with known capacity with an approximation factor of 0.405, where the approximation factor is the worst case ratio between the solution obtained by the algorithm and the optimal solution. We identify an universal policy that approximates the optimal solution to the submodular maximization problem with an unknown knapsack capacity at least as good as Wolsey's greedy algorithm approximates the optimal solution to the submodular maximization problem with a known knapsack capacity.

■ TA-20

Thursday, 8:30-10:00 - ESA W(est) 119

OR and the Global South 2

Stream: OR in Developing Countries
Invited session
Chair: *Gerhard-Wilhelm Weber*

1 - Fleet Sizing in the Humanitarian Sector
Laura Turrini, Nathan Kunz, Maria Besiou

A dramatic increase in humanitarian needs has led to calls for more benchmarking across humanitarian organizations (HOs) by donors urging them to share best practice and learn from each other to boost efficiency, even as their funding continues to decline. Benchmarking is particularly relevant to fleet management as vehicles are expensive assets that play a key role in program delivery. Unlike earlier research efforts that studied fleet management at the level of the individual organization, we consider multiple HOs and common drivers of fleet size, given that they often work in similar settings and with similar constraints. Challenging the view that comparisons are unrealistic, our findings from four HOs show that benchmarking is possible. We find that country fleet size depends directly on number of staff, number of locations, and the quality of road infrastructure, and indirectly on the population of concern. Factors such as the extent impact of disasters and income inequality have a moderating effect. Our contribution to fleet sizing literature lies in generalizing our findings to multiple (and very different) HOs, thus providing insight for benchmarking fleet size in various countries.

2 - Extension of the KEMIRA multi-criteria choice method to group decision making: the case of choosing the best varieties of a given crop for a region
Stéphane Aimé Metchebon Takougang, Naguiesmongho Christian Nana, Benoit Joseph Batieno

Most land use problems, such as the choice of varieties of a given crop for a region, are solved by considering a single decision maker. In the case where there are several decision-makers, it is often assumed that a consensus has been reached among them so that they all act as one decision-maker. To compensate for this single decision-maker view, literature propose several multi-criteria methods for group decision making. However, most of them suffer from certain limitations. On the one hand, a first limitation may be the large number of parameters to be determined during the execution of the decision process, which may be inherent to the method used itself. On the other hand, the difficulty of aggregating the preferences of each stakeholder, who are now all considered to be decision-makers, in order to arrive at a decision that can be accepted by all of them, constitutes the second limitation. In this work, we contribute to remedy these two limitations by proposing an extension of the existing KEMIRA multi-criteria choice method for group decision making. We illustrate the effectiveness of our approach through a case study of the selection of the best cowpea varieties (crop) appropriate to a given region in West Africa (Burkina Faso).

■ TA-21

Thursday, 8:30-10:00 - ESA W(est) 122

Deep Learning and Pre-Trained Forecasting Models

Stream: Analytics, Forecasting and A.I.
Invited session
Chair: *Sven F. Crone*
Chair: *Hans Georg Zimmermann*

1 - A pre-trained model for time series forecasting
Claudia Ehrig, Julia Schemm

Machine learning offers new opportunities to create more accurate and reliable forecasts compared to statistical methods. However, state-of-the-art machine learning models for time series forecasting are becoming more complex, demanding increasing training times. Whenever an application requires retraining, computational effort is multiplied. Pre-trained models may provide one solution to limit this effort and keep machine learning models applicable in practice. But finding appropriate source data is difficult and requires resources. We propose to use a deep neural network for time series forecasting pre-trained on various real-world and simulated time series data sets to be efficiently fine-tuned. We benchmark the pre-trained model against training from scratch for a wholesales demand forecasting use case regarding accuracy, uncertainty, and runtime.

2 - Deep Neural Networks for Shallow Results? An empirical evaluation on the benefit of customising Artificial Neural Network algorithms in industry forecasting
Sven F. Crone

The success of Deep Artificial Neural Networks (NN) in text, image, and speech recognition has led applications in various other disciplines, including forecasting. Long-Short term Memory Recurrent NN (Ma et al, 2015), Deep Belief NN (Kuremoto et al., 2014), and Structural Autoencoders (Gensler et al., 2016) are but few of the deep NN architectures promising increased accuracy over the established shallow multilayer perceptrons (Crone, 2010; Dudek, 2016). However, empirical studies by Markidakis et al, 2018 showed that standard deep and shallow NN fail to outperform statistical benchmarks on monthly industry datasets, and surveys in forecasting practice indicated that over 50% of all AI forecasting projects in industry fail (Crone, 2022). This study seeks to assess the this contradiction of deep NN by assessing the empirical accuracy across multiple real-world industry datasets in medical devices companies. We conduct a valid empirical evaluation across four companies and 5k time series, using reliable error metrics, multi-step ahead horizons and multiple rolling time origins to compare against statistical benchmarks in R (incl. ets, autoarima, theta), recent data science contenders (incl. Facebook's Prophet, Google's bsts), and machine learning methods (incl. XGBoost and random forests). We confirm prior results from standard NN model settings. However,

when presented with carefully customized NNs using feature engineering and metaparameter turning, both the shallow and deep NNs are be customised to outperform statistical, ml and data science benchmarks methods out of sample. We conclude that using „vanilla" deep or shallow NN implementations from R or python yields poor results, but careful customisation of features can significantly increase their efficacy.

3 - Deep Learning vs. Econometric Financial Time Series Analysis
Theo Berger

We provide an in-depth assessment of univariate daily financial time series analysis via machine learning and provide a thorough discussion beyond return predictability. We simulate economic time series and present an in-depth assessment of relevant hyperparameter tuning and discuss the ability of competing machine learning algorithms to capture econometric properties of financial time series. Also, we assess empirical data and provide a discussion on competing approaches in comparison with econometric benchmarks, when the data generating process is unknown.

As a result, we assess more than 50.000 in- and out-of-sample forecasts. Drawing on realistic sample sizes, we find that recurrent neural networks with one layer describe a superior alternative to econometric ARMA approach.

■ TA-24

Thursday, 8:30-10:00 - ESA O(st) 120

Scheduling applications

Stream: Project Management and Scheduling
Invited session
Chair: *Simone Neumann*

1 - Application of reinforcement learning to the Westenberger-Kallrath problem
Philipp Willms, Marcus Brandenburg

The nature of chemical processes imposes multiple challenges on production planning and scheduling. The classical Westenberger-Kallrath (WK) problem which was published in 2002 still serves as a benchmark for that industry. In the past, mathematical models and solution approaches made use of linear programming (LP) methods or metaheuristics. For recent years, approaches in the field of artificial intelligence (AI) have gained in popularity due to algorithmic advances and modern implementations. Nowadays, AI-based optimization provides new opportunities for integrated modeling and solution methods. In this research, we investigate the application of reinforcement learning (RL) and propose a novel approach to solve the WK problem. Specifically, we develop MRP and batching heuristic to preprocess the problem data and create chainlinks that can be scheduled independently. Next, we apply RL algorithms to train an agent to schedule the chainlinks following the objective to minimize the makespan of the complete schedule. The agent's performance is further evaluated by using a discrete-event simulation model. We detect modeling and implementation challenges, current limitations as well as future research perspectives on RL for production scheduling problems with complex material flows.

2 - Transportation Labor Cost Reduction via Vehicle Platooning
Florian Jaehn, William Caballero, Brian Lunday

The advent of automated and semiautomated driving technologies is prompting a reevaluation of the benefits of truck platooning. Whereas the effect of truck platooning on fuel costs is relatively well studied, automated driving enables further cost reductions in the form of labor savings that has, heretofore, been sparingly investigated. The degree to which such savings can be realized depends upon myriad factors. Foremost among them are driver payment policies and platoon formation procedures. Automated driving technology reduces the demands on a platoon's follower vehicles, which, in turn, justifies modified driver compensation structures. However, reductions in labor expenditures are often limited by load characteristics that inhibit platoon formation. Therefore, this research sets forth a suite of related truck platooning problems that correspond to alternative assumptions about unloaded-truck compensation and shipment temporal flexibility. The computational complexities of these problem variants are examined, NP-hardness is proved for the suite, and other useful mathematical properties are derived. Extensive empirical testing using the U.S. highway system explores the effect of network topology, commerce flow, and platooning labor savings on each problem's optimal solution, tractability, and other related metrics. Multiple heuristics are also designed and tested for larger-scale instances. In so doing, this research not only explores the effects of varied factors on platooning labor costs but it also provides practical means to identify high-quality, labor-cost-reducing routes.

3 - Analysis of Storage and Retrieval Processes in Compact Storage Systems
Yagmur Gül, Simone Neumann

In order to provide fast access times to the stored items in warehouses, different types of storage systems exist. A number of factors, including the physical size and weight of the items to be stored, the frequency of use, and the resources (such as space) available, will determine the type of system that is suitable for a particular warehouse. In this talk, we will examine a new type of storage system that was given little attention by the scientific community so far, the compact storage systems. Compact storage systems aim at achieving the highest possible space utilization rate given a limited storage space. Bearing is achieved by a three-dimensional grid of storage units (e.g., rectangular bins), which are picked and positioned by automated mobile robots. We want to shed light on the specifics of such storage systems and analyze how to optimize the storage and retrieval of items within them (e.g., by order picking and batching, the sequencing of the retrievals and control, navigation and relocation of storage units).

■ TA-25

Thursday, 8:30-10:00 - ESA O(st) 222

Simulation and Machine Learning

Stream: Simulation, Reinforcement Learning and Quantum Computing
Invited session
Chair: *Max Krueger*

1 - To couple models for cardiac electrophysiology with transparent interface conditions
Lea Strubberg

Mathematical models are useful for studying the effects of medications and diseases on the heart, but achieving both accuracy and computational efficiency is challenging. Highly precise models that can describe cardiac electrophysiology on a cellular level are computationally demanding and not practical for simulating a large amount of myocytes. On the other hand, efficient models may lack accuracy and are not suitable for all applications, such as when modelling cardiac fibrillation or arrhythmia. A spatial coupling of cardiac models can combine the benefits of both by using a precise model for parts of the tissue that require high accuracy, such as scar tissue, and an efficient model for the remaining tissue, thereby reducing computational costs. However, this coupling creates an artificial interface between the models that requires the definition of boundary conditions. The question is how to define these conditions so that the interface becomes as transparent as possible when simulating the tissue as a whole.

To address this problem, we will focus on two macroscopic models: the monodomain and the eikonal model. By solving the eikonal model at each time step of the monodomain simulation, we can interlink the information they provide and obtain a transparent coupling scheme.

2 - Cross Validation of Random-Forests' Classification Performance in Maritime Scenarios with Aggregated AIS Messages
Max Krueger

In the early 2000s, AIS (Automatic Information System) became mandatory for almost all seagoing vessels, which have to broadcast ship's tracking and navigational information for collision avoidance and maritime safety. Maritime surveillance agencies can use AIS data for the classification of vessels, e.g., for the detection of spoofing behavior in fishery scenarios. This contribution looks at detecting Fishery

type behavior by Random Forests based on aggregated AIS messages. It addresses the question of how much classification performance, measured by accuracy, depends on the geographical features in training datasets of AIS data rather than on general fishery vessels' properties. For this purpose, Random Forests are trained on aggregated real-life AIS data for fishery detection in different maritime areas and cross-validated against each other.

3 - Control of shared material buffers in stochastic flow lines
Nora Krippendorff, Christoph Schwindt

Flow lines are the most prevalent configuration of manufacturing systems for high-volume discrete parts production. A flow line comprises several workstations that are arranged in series according to the sequence of operations to be executed. In mixed-model production, the lines are typically run in unpaced and asynchronous mode by placing material buffers between consecutive machines to reduce blocking and starving phenomena and hence increase the system's throughput. The production rate of an unpaced line can be further increased by substituting the dedicated for shared material buffers, which are assigned to different machines. The additional flexibility allows for an increase in contribution margins for finished products, but also comes with supplemental conveyance cost incurred by material transfers between machines and buffers. In this talk, we consider a control problem arising in stochastic flow lines with shared buffers. Sharing buffer capacities among machines presupposes a set of decision rules that determine the types and timings of material transfers. The buffer control problem consists in finding a transfer policy maximizing the expected gain rate of the system. Assuming a Markov line in steady state, we explain how the problem can be modeled as a continuous-time Markov Decision Problem. As a result, the search for an optimal policy can be limited to deterministic and stationary event-driven policies. Moreover, we review a uniformization approach, which yields an equivalent representation in discrete time, and present a reinforcement learning solution method.

4 - Improving the scheduling of AGV and AMR using simulation
Maximilian Dilefeld, Thorsten Claus, Frank Herrmann

Automated Guided Vehicles (AGV) and intelligent Autonomous Mobile Robots (AMR) are an important tool for designing a flexible Industry 4.0 shopfloor. Both types of Mobile Robots are usually deployed with a Fleet Management software to manage (transport) orders and vehicles together with other superordinate control systems. The planning tasks in the superordinate control system used by both AGVs and AMRs can be divided into Material Flow Management, Job Management, Vehicle Dispatching and Job Processing. Requests for supply and removal of material is issued by the stations and has to be combined to transport jobs. Alternatively, more complex system often user external Material Flow Controllers (e.g. MES). Jobs are collected in a queue and their execution order is determined. Vehicles which can execute the next job have to be identified and the best one is selected. Jobs are split into smaller tasks which are sent to the Mobile Robot and executed. For AGVs navigation functions are mostly integrated into the Fleet Manager as part of the Job Processing, while AMRs perform lower-level navigation functions directly on the vehicle and use the superordinate control system for implementing restrictions and traffic control functions. A need for further research and development was identified especially for decision-making algorithms within the Fleet Management. The goal is to compare existing and develop new strategies to solve the different planning problems. For the individual planning tasks different techniques have been discussed and used in research and practice. However, there is no universal best solution and different options must be compared in the context of the specific use case.

Thursday, 10:30-11:30

■ TB-02

Thursday, 10:30-11:30 - ESA B

Tutorial by Gurobi

Stream: PC Stream
Tutorial session
Chair: *Silke Horn*

1 - Gurobi in the Python ecosystem
Silke Horn, Robert Luce

In this tutorial, we will guide you through the integration of Gurobi with the greater Python ecosystem. We will demonstrate model-building patterns based on NumPy and SciPy.sparse data structures and how to take advantage of indexed DataFrames and Series in pandas. Furthermore, we will show how to use trained regressors from scikit-learn as constraints in optimization models. Join us as we delve into the world of optimization with Gurobi and elevate your Python-based workflows.

■ TB-06

Thursday, 10:30-11:30 - ESA C

Semi-plenary talk Klimm

Stream: PC Stream
Semi-plenary session
Chair: *Guido Voigt*

1 - Information design for congested networks
Max Klimm

We consider a largely untapped potential for the improvement of traffic networks that is rooted in the inherent uncertainty of travel times or demands. As this data is subject to stochastic uncertainty resulting from various parameters such as weather condition, occurrences of road works, or traffic accidents. Large mobility services have an informational advantage over single network users as they are able to learn traffic conditions from data. A benevolent mobility service may use this informational advantage in order to steer the traffic equilibrium into a favorable direction. The resulting optimization problem is a task commonly referred to as signaling. We tightly characterize the class of single-commodity networks, in which full information revelation is always an optimal signaling strategy. Moreover, we construct algorithms computing the optimal signaling scheme whose complexity is polynomial in the number of support vectors that arise in the equilibrium. While this number may be exponential in worst-case instances, it is relatively small in realistic instances. Using a cell decomposition technique, we obtain a polynomial-time algorithm for multi-commodity parallel edge networks with a constant number of commodities, even when we have a constant number of different states of nature.

■ TB-07

Thursday, 10:30-11:30 - ESA J

Semi-plenary talk Brailsford

Stream: PC Stream
Semi-plenary session
Chair: *Katja Schimmelpfeng*

1 - Improving emergency care using a new approach to generic simulation modelling
Sally Brailsford

One of the well-known barriers to the widespread use of modelling in healthcare is the 'not invented here' problem. Managers and clinicians trust models that they were actively involved in developing, but do not necessarily trust models developed for other settings. Unfortunately, generic models designed to be applicable anywhere face their own challenges. Potential users may distrust this one-size-fits-all approach, and tailoring a generic model to a specific site may require technical modelling skills and the purchase of costly software. This talk presents a new approach to tackling these challenges: initially developing a user-friendly, cloud-based, 'semi-generic' model based on a set of hospitals in one particular region, and then modifying the model to make it fully generic. The approach is illustrated by a system dynamics simulation model that allows a novice user to test the system-wide impact, in their own locality, of five Emergency Department based interventions targeted at older people. The talk briefly describes the model, but focuses mainly on the processes of model development, piloting, and dissemination, concluding with a discussion about whether this new approach is likely to improve the chances of wider adoption across the UK National Health Service.

Thursday, 12:50-14:20

■ TC-02

Thursday, 12:50-14:20 - ESA B

Decision support for decarbonization in integrated energy systems

Stream: Decision Analysis and Support
Invited session
Chair: *Christoph Weber*

1 - Exploring different decarbonization pathways for chemical sites
Tobias Korte, Valentin Bertsch

The decarbonising of the industrial sector is a major task for the coming years and decades, with CO2 emissions from chemical sites playing a significant role. However, the overarching goal of increasing the share of renewable electricity that is fed into a chemical site's utility infrastructure imposes multiple challenges, one of them being the conflict that arises from the stochastic nature of renewable energy, which does not directly match the continuous nature of most chemical processes. In this regard, solutions need to be explored and technologies such as high temperature heat pumps and steam gas turbines (H2/O2 combustion) are identified as potential technologies that can contribute to the decarbonisation of the process steam supply. These technologies are implemented into an existing framework for chemical sites, called ideal-typical utility infrastructure (iUI). Here, in the base implementation of the iUI, the process heat generation highly relies on the combustion of natural gas in gas turbine and gas boiler units. Therefore, this work explores different iUI expansion pathways that focus on generating process steam in a less CO2 intensive manner. These pathways are investigated and evaluated using the highly adaptable open-source energy system modelling framework SpineOpt. A special focus is on the use of waste heat from industrial processes, which can serve as a heat source for heat pumps. Different pathways are compared with respect to various criteria such as system costs, decarbonisation potential and practical feasibility.

2 - Accounting for seasonal storage dispatch in expansion planning of integrated power and gas systems via Benders Decomposition
Julian Radek, Daniel Brunsch, Christoph Weber

The integration of hydrogen technologies is expected to play a vital role in the decarbonization of the energy system. To account for the interdependencies between the electricity and gas sector, integrated modelling approaches for long-term expansion planning are necessary. Comprehensive models that optimize the investment decision endogenously and determine the dispatch of generation units and flexibilities on a high regional and temporal granularity are hardly solvable in reasonable time. To overcome this obstacle, decomposition techniques are commonly used as well as a reduction of the temporal level of detail by using typical time periods instead of a whole year in hourly resolution. While most of the dispatch decisions can be made by optimizing typical weeks independently, seasonal hydrogen storages are managed over longer time frames. So, the optimization framework has to account for the seasonality of storage fillings levels. In this work, a Benders Decomposition approach is applied to decompose an energy system planning problem into a master problem, where the investment of electrolyzers and gas storages is determined, and separate subproblems for the operational optimization of the power and gas sectors. To reduce complexity, only typical time periods are used in the subproblems. Based on an approach by Kotzur et al. (2018) for seasonal storage optimization, an approach is developed that optimizes the transition between typical periods in the master problem. Along with endogenously determined capacities, information about filling levels is transferred to the subproblems, where the short-term storage dispatch is optimized . That is, the typical periods in the subproblems remain independently of each other which reduces complexity and enables parallelization.

3 - Towards a Cross-Sectoral Energy System Operation: A Distributed Market-Clearing Framework for Electricity and Gas Systems
Aiko Schinke-Nendza, Christoph Weber, Antonio Conejo

To achieve Europe's climate-neutrality goals by 2050, energy systems have to undergo significant changes. Decarbonization requires expanding fluctuating renewables and cross-sectoral solutions, such as power-to-gas. Decentralization, driven by small-scale renewables, strains infrastructure, demanding investment for expansion and flexibility. Simultaneously, digitalization enhances communication and coordination in the sector, offering vast opportunities. Addressing these challenges of a decentralized and decarbonized future energy system, we propose a novel framework for improving short-term operational coordination between electricity and natural gas markets, while taking advantage of the ongoing digitalization. Based on decomposition techniques, our approach enables individual units, particularly small-scale renewable units and coupling units between electricity and gas systems, to participate in a distributed and iterative market-clearing procedure, going beyond current single-bid auction schemes: each entity, either unit or network operator, iteratively optimizes itself and communicates with physically connected neighbors exclusively, i.e., exchanging offers and bids. Therefore, the confidentiality of commercially sensitive data of both, units and network operators, is preserved, while an optimal operation of a cross-sectoral energy system can be achieved. We assess the framework's reliability and scalability using a tractable polyhedral convex relaxation of the natural gas system and demonstrate its capability to consider natural gas pipeline flexibility together with its linkage to renewable generation and electricity system congestion. We apply the framework to the German electricity and gas system, evaluating its computational effort and performance.

4 - Accelerating the Energy Transition: Determining No-Regret Transition Pathways in the Port of Rotterdam
Jaron Davelaar, Nort Thijssen, Rutger de Mare, Marian Bijl

Industrial clusters like the Port of Rotterdam face a major challenge: lower CO2 emissions by 55% in 2030 and by 100% in 2050 compared to 1990. In the development of regional strategies a large set of stakeholders are involved. Quite often they await each other's key decisions. Another important challenge is how to best develop incentive schemes to be proposed by governments such that stakeholders jointly move towards efficient investments. To support this process, a Quo-Mare propriety tool called TEACOS (Techno-Economic Analysis of Complex Options Spaces) is used. The scope for the Rotterdam model consists of 35 industrial companies and 14 power producers, currently emitting 29 Mt/a CO2. This scope is complemented by an infrastructure network, consisting of the electricity, natural gas, CO2 and hydrogen network. Decarbonization options for each industry in the cluster (energy savings, CCS, hydrogen, electrification) are included in the model. The model ensures that all of the above decision elements are addressed in a structured manner. The large option space calls for a structured methodology to ensure appropriate timing of investments. The model is data-driven and based on a Mixed-Integer Multi-Period Linear Programming algorithm. TEACOS evaluates the impact of integer decisions (decarbonization & infrastructure investment options) simultaneously with continuous variables (interconnecting flows) subject to various constraints (like CO2 targets). The objective is to maximize the Net Present Value of the accumulated Margin. The scenarios focus on the acceleration of the energy transition, the infrastructure needs & the role of different decarbonization strategies. TEACOS is a trilemma-solver, which brings together industry, network operators and governments.

■ TC-03

Thursday, 12:50-14:20 - WiWi A, VMP5

Exploring Challenges and Solutions in Modern Logistics: Adaptive Search, Mobile Operations, and Zoning

Stream: Logistics
Invited session
Chair: *Riccardo Tronconi*

1 - Adaptive Large Neighborhood Search for a real-world dial-a-ride problem with multiple depots and heterogeneous working shifts
Riccardo Tronconi, Francesco Pilati, Karl Doerner

Many people have regular treatments at the hospital and they have to be transported by transport services. As the demand is increasing existing systems are inadequate to meet the actual demand and deal with high operating costs and, thus, there is the need for reliable and efficient transportation systems. In the literature, the transportation of dependent people is very often modelled as the dial-a-ride problem and has been widely studied along the last few years. We extend the dial-a-ride problem in three aspects: we have a heterogenous fleet, multiple depots and different working shifts of the crew. The last feature affects the problem modelling since not all the vehicles are available during the entire working period and, thus, the transportation requests should be assigned to available vehicles if possible. The objective functions consider three aspects which have to be minimized. The first one is the total travel time which can be converted in an economic aspect since drivers are usually distinguished by a time-based cost. The second one is the total waiting time, related to the patients inconvenience, and the third aspect is related to the drivers conditions and the total working shift violation. The enriched dial-a-ride problem is solved through an adaptive large neighborhood search metaheuristic characterized by tailormade destroy and repair operators. The algorithm provides good results for standard instances and for real-life problems.

2 - A fix-and-optimize approach for the integrative zoning and item-to-zone assignment in pick-and-pass order picking systems
Regina Thelen, Ralf Gössinger

Order picking is the logistic warehouse process of consolidating stored items according to customer orders. Pick-and-pass systems are zoned systems in which each picker only works in one storage zone and each zone only comprises a sub-set of items. Hence, order-related containers are routed along a sequence of zones to be filled up with the items needed for order fulfillment. When designing a pick-and-pass system, two organizational questions need to be answered: How should the zones be formed and which item should be assigned to which zone? Answers to these questions can be given by solving corresponding optimization problems. Since both problems are strongly interrelated, we developed an integrative decision model that simultaneously determines zone size and item-to-zone assignment. Based on a full-factorial numerical study, we found that the model correctly reflects the planning situation. Due to its high complexity, the model can only be solved exactly for very small problem instances in an acceptable time. This motivates the use of solution approaches, which achieve near-optimal solutions with reasonable computational effort. In the intended paper, we adapt the fix-and-optimize approach to solve the integrative zoning and item-to-zone assignment problem heuristically. Starting from an initial solution, the heuristic iteratively solves different sub-problems where a part of the decision variables is fixed. We analyze how the performance of the heuristic can be improved by generating the initial solution, specifying a fixation strategy, and limiting the number of iterations. To this end, we develop variants of the fix-and-optimize approach and conduct a numerical study in which the performance of the variants is compared with each other and with the exact approach.

3 - Rethinking cyclic structures in liner shipping networks
Daniel Wetzel, Kevin Tierney

Liner shipping networks are a central feature of modern supply chains that consist of cyclical, periodic services operated by container vessels. This specialized, cyclical structure eases planning for both shipper and carrier, but the combination of cyclical planning with the available time windows at ports can lead to inefficient operations. We propose to relax the cyclical assumption and allow vessels to move between services to avoid inefficient connections without interruption to container flows. From the view of a shipper, the cyclical and periodic properties of the services still hold, and the liner carrier can offer a more efficient overall network. The ensuing optimization problem consists of a combined vessel routing problem and cargo allocation problem, resulting in large and challenging instances. We model the problem using mixed-integer linear programming and use an expanding horizon heuristic to find starting solutions for our model. Our use of real-world data demonstrates that introducing flexibility into a liner network can lead to significant cost reductions compared to standard cyclical schedules.

4 - A Heuristic for Planning Mobile Parcel Locker Operations with Individual Customer Service
Ninja Soeffker, Rico Kötschau, Jan Fabian Ehmke

The ongoing growth of e-commerce deliveries has led to a significant increase in last-mile delivery volumes. New technologies are being investigated to provide these deliveries efficiently and in a customer-friendly manner. In this paper, we investigate mobile parcel lockers which can be parked for temporary collection of items at different locations, keeping the pickup distance to the customer short and avoiding

high infrastructure costs. Mobile parcel lockers combine the possibilities of serving multiple customers with a longer stop if they indicate a willingness to walk and the delivery to conservative or remote customers with shorter stops at their doorstep. The objective is to maximize the number of served customers with a given fleet of mobile parcel lockers, considering which customers should be served individually at their doorstep (attended home delivery service) and which customers are served collectively through pickup points (mobile parcel locker service). We present heuristic approaches to solve this problem efficiently and analyze the characteristics of attended home delivery and mobile parcel locker customers.

■ TC-04

Thursday, 12:50-14:20 - WiWi B1, VMP5

Exploring Advances in Vehicle Routing and Logistics: Anticipatory Acceptance, Auction-Based Exchanges, and Batching Integration

Stream: Logistics
Invited session
Chair: *Jonas Winkelmann*

1 - Assessing interventions to foster heavy-duty alternative fuel vehicle adoption leveraging approximate dynamic programming

Jonas Winkelmann, *Stefan Spinler*

More and more logistics companies have started to renew their fleets with alternative fuel vehicles (e.g., Amazon, DHL). However, heavy-duty truck operations are lagging behind, as available technologies (e.g., BEVs, FCEVs) do not fully meet the requirements yet. Moreover, while the path towards climate-neutral transportation is more or less clearly outlined for passenger cars and light-duty vehicles, the heavy-duty segment lacks clear commitments of producers or strong guidance through political regulation. How can a transition toward sustainable mobility be fostered in a heavy-duty truck fleet? Which political and company-internal interventions are most likely to be effective? We aim to provide a perspective on these questions by leveraging simulation and optimization. We model the fleet renewal of heavy-duty transport companies as a large-scale sequential stochastic problem, considering uncertain truck purchase prices, energy prices, battery prices, and carbon prices. Approximate dynamic programming is proposed to derive policies on when to purchase and sell which vehicle drivetrain technologies to minimize the total cost of ownership. We leverage the approach to evaluate the effectiveness of 15 different interventions (e.g., street bans, emissions targets, R&D funding) and multiple combinations of these interventions for three types of operations (short-, medium-, and long-distance). At the conference, we aim to present our approach and first results.

2 - Auction-based Exchanges in Parcel Logistics: Empirical Bounds for the Second Price

Christian Truden, *Margaretha Gansterer*, *Dario Paccagnan*

Horizontal cooperation among parcel carriers, i.e., the exchange of parcels, can be an effective means to reduce vehicle emissions while saving delivery costs. We propose setting up a Vickrey-Clarke-Groves (VCG) auction that shall organize the exchange of parcels among carriers such that the overall vehicle emissions and delivery costs are reduced. However, the VCG mechanism is prone to overspending, i.e., paying the winning bidder significantly more than necessary, which is only limited by the second price. This property is potentially problematic for parcel auctions as the available amount of money is limited by the collected delivery fees. In a numerical study, we quantify the premium of the VCG mechanism in a practical setting.

3 - Real-World Warehouse Batching at Zalando: Integrating item assignment into order batching and routing

Julius Pätzold, *Imran Khan*, *Olaf Maurer*, *Paweł Pszona*, *Jan-David Salchow*

Order Batching algorithms are a well-researched topic in the area of warehouse and logistics optimization. They solve the problem of combining customer orders into groups (batches) that are then picked by warehouse pickers. Literature provides a variety of different batching problems, for example by distinguishing between online and offline order pools, different objective functions (pick time vs. lead time), different types of orders (single vs. multiple order positions) and more.

In this talk we will give an introduction to a specific batching problem that we are working on at Zalando. While this problem includes 1) Grouping of customer orders into batches, and 2) Splitting of batches into route-optimized picktours, we want to put emphasis on a third sub-problem: 3) Assignment of order positions to physical warehouse items. Sub-problems 1) and 2) are well-researched in the literature, even as a combined problem, but the assignment of order positions to warehouse items is often assumed to be a fixed input.

The scope of our presentation is to give a problem description of the order batching and routing problem that includes assignment of positions to items. Next to providing a more in-depth explanation of the proposed problem, we also provide a solution algorithm and present computational results on benchmark instances.

4 - Anticipatory request acceptance in dynamic and collaborative vehicle routing

Yannick Scherr, *Margaretha Gansterer*, *Richard Hartl*

We consider the problem setting of a less-than-truckload carrier fulfilling stochastic customer requests. Requests arrive over time and must be immediately accepted or rejected. On the next day, the requests are served in routes using a fleet of vehicles with limited load capacity and route duration. To achieve individual cost savings and reduce broader effects of transportation such as emissions or traffic, a carrier may seek horizontal collaboration with other, similar carriers. In the considered setting, participating carriers exchange a subset of their accepted requests in a combinatorial auction after the request acceptance phase and before the requests are fulfilled. Carriers place bids on bundles of requests, then an auctioneer allocates the bundles to carriers in a cost-minimizing way and distributes the auction profits. Each carrier's optimization problem of maximizing profit can be modeled as a Markov decision process that comprises the sequential decisions in all phases, i.e., request acceptance, request selection for the auction, bidding, and routing. Heuristic approaches are proposed to generate preliminary route plans and for considering the options provided by the auction already when making request acceptance decisions. We specifically study overbooking policies for accepting more requests than can be served before the auction takes place and the strategic rejection of requests in anticipation of more profitable upcoming requests. Numerical experiments show that carriers' request acceptance decisions impact their individual profits and the overall collaboration savings. The largest benefits can be achieved with an overbooking policy that is applied by all carriers and considers the locations of both the request and the carriers' depots.

■ TC-06

Thursday, 12:50-14:20 - ESA C

Food supply chains

Stream: Supply Chain Management
Invited session
Chair: *Moritz Kettele*

1 - Simulation optimization to evaluate the effects of horizontal cooperation on the resilience of short food supply chains

Suad Saliju, *Christian Fikar*

Short food supply chains (SFSC) are often perceived as a solution towards more sustainable and resilient food systems. At the same time, however, an increasing number of disruptions, caused by various natural hazard events and man-made disasters, have seen food supply chains severely affected. While the impact of disruptions on various supply chains has been extensively investigated in the literature, there is still a lack of research regarding their impact on SFSC. Given the current energy crises and as a result, potential blackouts and increases in energy prices, numerous farmers are expected to be affected by such disruptions, with the effects to be felt even stronger by smallholder farmers. The purpose of this work is therefore to study the

impact of such disruptions on SFSC and to evaluate if and to what degree, could joint coordination and cooperation strategies facilitate resilience. For this, a decision support system (DSS) is developed using a hybrid optimization-based simulation model. The model developed incorporates both resilience, through the evaluation of various mitigation strategies, and sustainability, in terms of total post-harvest traveled distances and food losses. The DSS is demonstrated on a regional asparagus supply chain in the Franconian region, in Bavaria, Germany. Results highlight the importance of joint activities to both, facilitate resilience and reduce food losses.

2 - A Global Food Supply Chain for Two Agricultural Products: A case study from an economic point of View

Mani Bakhshi Sasi, Ruhul Sarker, Daryl Essam

Currently some food products are produced in some specific regions that must be distributed to other regions for fulfilling demands on time, which highlights the role of international trade such as import and export. To plan the distribution of these products, we introduce the global food supply chain (GFSC) problem that involves complex economic and agricultural constraints. In this paper, an integrated Linear Programming (LP) model is developed for the combined rice and wheat supply chain. The model aims to optimize the flow of rice and wheat within the trading partners of these products in the global context. In doing this, constraints are also imposed on production, exports, imports, storage, budget, and flow capacity. Depending on the current import trend, assumptions are made about the purchasing ability of the countries with a focus on imports, including their Gross Domestic Product (GDP). Thus this paper also analyses the proposed GFSC from an economic point of view. To show the model's applicability, a real-world case study is conducted, that includes most countries in the world. The data were collected from different publicly available sources and prepared as inputs to the model. The developed LP model was solved using the CPLEX solver of the GAMS software. The results are analysed and compared to the current distribution scheme. The analyses uncover interesting insights into the global supply chain of rice and wheat and the potential of issues of countries in economic growth or decline.

Co-authors: Ruhul Sarker, Daryl Essam

3 - Simulating strategic, tactical, and operational decisions to assess resilience of food supply chains facing disruptions

Moritz Kettele, Gernot Lechner, Rupert Baumgartner

The occurrence of disruptive events, such as the Covid-19 pandemic, necessitates a greater emphasis on resilience management for supply chains and their associated actors. Especially food supply chains (FSC) play a vital role in ensuring food security. Therefore, FSC actors need to strategically prepare for disruptive events while having tactical and operational plans in place once a disruption hits to mitigate its impacts. With this in mind, this study aims to compare different resilience strategies on multiple decision levels using simulation and acquire insights into FSC resilience for future disruptions.

This paper follows a three-step research design to identify, simulate and assess resilience strategies: (1) screen existing literature to identify strategic, tactical, and operational resilience strategies, followed by (2) the identification of intervention points along a FSC and recommendations for the implementation in simulation models, and (3) the integration and comparison of the identified strategies applying discrete-event simulation for various disruptive scenarios.

Based on empirical data from the Austrian dairy supply chain, the preliminary findings compare six resilience approaches in two disruptive scenarios indicating the importance of operational adaptions and capacity redundancies. Decision makers must also consider combining various approaches from different decision levels. Moreover, it is crucial to observe the long-term effects of the approaches once the disruption is over.

This research fills a gap by incorporating operational, tactical, and strategic decision-making in FSC resilience simulations. The contributions are to the field of FSC resilience and extend simulation applications in supply chain disruption management.

■ TC-07

Thursday, 12:50-14:20 - ESA J

Risk Management

Stream: Financial Management and Investments
Invited session
Chair: *Charlotte Neuss*

1 - Does the Stock Market Care about Firms' Risk Management and Risk Management Disclosure?

Charlotte Neuss, Andreas Oehler

We examine the relationship between firms' risk management and idiosyncratic volatility. We analyze their annual reports and compare two proxies of risk management: the keywords for the steps in the cybernetic cycle of risk management and the implementation of an enterprise risk management (ERM) system. We hypothesize that the disclosure of risk management reduces idiosyncratic volatility. The analyzation is based on stocks listed in the German CDAX index between 2002 and 2020. Firms that report several steps in the cybernetic cycle of risk management show significantly lower idiosyncratic volatility. Furthermore, disclosing the steps in the cycle has a significantly negative relationship with the idiosyncratic volatility in the next year. We do not find a significant relationship between disclosure regarding the implementation of the ERM and idiosyncratic volatility. These findings indicate that the market perceives the ERM as less important than convincing information about a fundamental process for managing risk including details such as the steps of identification, measurement, adjustment, and control of risks.

2 - Optimizing cash withdrawal locations in the event of a crisis

Laura Brouer, Markus Weissenbäck

In the event of crises such as natural disasters, blackouts or pandemics, a stable and reliable supply of cash is essential to maintain the economic cycle. However, especially in crisis it is often no longer possible to guarantee the functionality of all cash withdrawal points, for example due to limited resources or reduced staff at cash-in-transit providers. Therefore, it is necessary to identify the optimal, most relevant withdrawal facilities to ensure an equitable supply of cash. This knowledge can be used tactically to prepare for a crisis, for example by placing emergency generators at relevant ATMs. During a crisis, it allows us to prioritize important withdrawal points and ensure a fair coverage of cash.

For this purpose, we develop a mathematical optimization algorithm based on solving a set covering problem with a variable radius. Using only open source geospatial data and individually adjustable parameters, the algorithm works independently of any existing database. We assume that the current withdrawal point coverage serves as a proxy for the corresponding population density and thereby need for cash. To preserve those geographical differences in coverage during crisis, individual sets of alternatives are determined for every ATM and bank. The algorithm identifies the minimal amount of withdrawal points for optimal coverage within the chosen crisis parameters. This approach can be expanded in the future for other types of cash withdrawal points, such as supermarkets. We evaluate the algorithm for several scenarios and analyze the influence of different parameters such as maximum distances, definition of alternatives or consideration of bank affiliation.

3 - Scenarios of systemic risk

Sebastian Schlütter, Philipp Aigner

In the risk management of financial institutions, the gradient (or Euler) capital allocation can support decision-making and optimizing the risk-return position. For Expected Shortfall, the gradient allocation is also called "Marginal Expected Shortfall" and coincides with the expectation vector of segment returns conditioned on the firm's aggregate loss exceeding the Value-at-Risk (cf. Hong and Liu 2009).

Acharya et al. (2017) apply the concept of (Marginal) Expected Shortfall to measure how individual institutions contribute to systemic risk. The authors also derive a tax which shall internalize the social costs of systemic risk and thus enhance social welfare.

Our paper shows that limitations known from the corporate risk management literature are also relevant for SES in the context of systemic risk. The condition underlying the calculation of SES—the financial market being in distress—corresponds to a snapshot of the strategies currently chosen by financial institutions. Using a stylized example,

we show that introducing the SES-based tax does not necessarily guide firms to the social optimum.

In order to measure contributions to systemic risk more meaningfully, we suggest using orthogonal convexity scenarios (OCS) as introduced by Aigner and Schlütter (2023). OCS generalize principal component analysis and extend the linear predictive power of the gradient allocation by second-order effects. We define a corridor of firms' portfolios within which the SES is a useful basis for taxation. Once firms' strategies move out of the corridor, regulators have to recalibrate the tax as well as the corridor. We also provide an empirical investigation and identify groups of firms with an increased potential to make a recalibration of SES necessary.

■ TC-08

Thursday, 12:50-14:20 - ESA M

Reverse and uncertain supply chains

Stream: Supply Chain Management
Invited session
Chair: *Osman Kulak*

1 - Operational strategies for mobile phone refurbishment

Osman Kulak, Martin Grunow

The market for refurbished phones provides significant opportunities for the efficient use of limited resources and grows rapidly. In such a supply chain system, purchasing, refurbishment, and sales are directly affected by a dynamic environment with fluctuating prices and demands. To provide purchasing, refurbishment, and sales strategies, we propose a linear programming formulation. We investigate how the sales price variation, purchasing price variation, correlation between sales and purchasing prices, limited semi-finished and finished goods inventories, and refurbishment capacity affect the considered supply chain for refurbished phones. Our numerical experiments use industry data and lead to important managerial insights for our industry partner.

2 - Designing Closed-Loop Supply Chains for Clean Manufacturing: Investigating Reverse Flow Practices and Collection Mechanisms

Ali Zahedi, Eva Selene Hernández Gress

Due to an enormous growth in resource usage and environmental pollution, returning the end-of-use product to use cycle is received wide attention. A closed-loop supply chain can reduce virgin resource usage and environmental impact and achieve economic benefit by returning waste and end-of-use products to the use cycle. This study examines the significant practices such as recycling, remanufacturing, reusing, reducing, and recovering considering material type and material recyclability. Especially, the impact of raw material types and their recyclability on recycling amount, resource usage, and environmental pollution are investigated. Effectively, a MILP multi-objective model is formulated with total cost as an economic benefit and material management as an environmental benefit. Finally, the correctness of the proposed model is verified by a case study of the beverage industry in Mexico City using the augment epsilon constraints method. We analyze the proposed model in three aspects including material types, recycling rate, collection mechanism, and return rate. The findings demonstrate that the manufacturing supply chain could tend to enhance the recycling amount when the operation recycling cost decrease and the recycling rate increase. Additionally, improving the collection mechanism could increase reverse value to achieve economic and environmental benefits. The research also extends the understanding of closed-loop supply chains by defining the important reverse flow practices and collection mechanisms for manufacturing enterprises.

3 - Dual sourcing in newsvendor models with an unreliable supplier and flexible order quantities

Dimitrios Pandelis

We consider newsvendor models with a primary supplier characterized by random capacity with known distribution. To hedge against the uncertainty associated with this supplier, the retailer can also procure from a reliable but more expensive supplier under a contract according to which he is allowed to return a portion of the order after the delivery by the primary supplier. We characterize the optimal orders for the cases of deterministic demand and random demand with known distribution. We also present numerical results that provide interesting insights into the effect of various model parameters on the optimal order quantities.

4 - Analysis of a multi echelon supply chain with parallel processing, multiple part types of products and external demand

Stelios Koukoumialos, Angelos Kourepis, Alexandros Diamantidis

This paper examines a push-pull system with multiple part types and external demand. An unreliable upstream machine may produce three different types of products that are stored to a different area (according to their part type) of a downstream buffer of limited capacity. The production rate is different for each product type that is processed by the upstream machine. It is also assumed that whenever the machine is repaired after a failure, it produces again the same product type that was produced when the failure occurred. Downstream to the buffer, a distribution center (DC) with parallel identical reliable machines/channels performs another final operation on the products. The finished products, according to their part type are stored in a separate dedicated area (Buffer of Finished Products). Customers arrive to the system according to a Poisson process (different for each product type) that is used to model the external demand and remove products from the appropriate Buffer of Finished Products. The upstream machine has exponential service, failure and repair rates, while the identical reliable machines/channels at the DC have exponential processing rates. The considered system is modeled as a continuous-time Markov process with discrete states. An algorithm that generates the transition matrix for any value of the system parameters is developed and all possible transition equations are derived and solved analytically. When the transition matrix is known, the performance measures of the considered model can be easily evaluated.

■ TC-09

Thursday, 12:50-14:20 - ESA O(st) 221

Optimal Control Theory and Applications

Stream: Continuous and Global Optimization
Invited session
Chair: *Andrea Seidl*

1 - Optimal vaccination policy in an epidemiological model with waning immunity

Vladimir Veliov

The talk will present an immuno-epidemiological model that captures the basic dynamic features of immunity acquisition and wane after infection or vaccination and analyzes its dynamical properties. The model consists of first order partial differential equations with different transfer velocities. For this reason, the proved existence of a solution is novel and non-trivial. The asymptotic behaviour of the model is analysed using the obtained qualitative properties of the solution. An optimal control problem with objective function including the total number of deaths and the costs of vaccination is explored. Numerical results of comarative analysis will be presented and discussed.

The talk is based on a joint paper with G. Angelov, R. Kovacevic, and N. Stilianakis

2 - Institutional change, education and population growth: lessons from dynamic modelling

Andreas Novak, Franz Wirl, Gustav Feichtinger

The contribution of this paper to be one of the first papers that links population growth, education and institutional change within a dynamic optimization. The basic premise is, following interesting papers of Boucekkine with different coauthors dealing with the Arab Spring, that elites manage first the ruling and then the transition to a 'democratic' government. We are less optimistic concerning the economic efficiency of domestic resource use and more important, extend this framework by accounting for (endogenous) population growth. These extensions render the survival of any elite much less feasible than already in models without population growth. Only a (cynical) elite worrying about the size of the population allows for a longrun and interior

outcome. Therefore, the rulers and the elite have to account for a second phase in which they lose control over a country's (financial) resources. If the elite lacks sufficient stakes in the second phase, it will 'take the money and run', i.e., no investment, at least close to the (endogenous) terminal time.

3 - Innovation and Product Positioning

Andrea Seidl, Richard Hartl, Peter Kort

In todays' economy, firms need to be innovative to survive. In the present talk we consider the problem of a firm which needs to decide about its investments into its knowledge capital to achieve an innovation breakthrough. Consumers are assumed to be heterogeneous with respect to appreciation of the product and the firm needs to decide on how to position its product with respect to the quality level. We start by discussing a static version of the model in which we are able to analytically determine the optimal investment sizes. We then present an optimal control extension where the firm invests into the knowledge capital in the first stage. In the second stage, the firm sells it product, however, the second stage only starts when a breakthrough occurs. We determine the optimal output price as well as the optimal R&D investment policy.

■ TC-11

Thursday, 12:50-14:20 - ESA H

Power-to-Gas

Stream: Energy and Environment
Invited session
Chair: *Hannes Hobbie*

1 - Impact of Spatial Electrolyzer Allocation in the Central European Energy System

Christian Perau, Manuel Ruppert, Wolf Fichtner

In recent years, the increasing share of generation from renewable energy sources poses challenges of grid congestion and renewable curtailment in the European Energy System. The volatile characteristics of renewables, especially wind and photovoltaics, require additional short- and long-term flexibilities in the system. Here, Power-to-Gas, which transforms electricity into hydrogen via electrolysis, is one option for long-term storage. Subsequently, other derivatives can be generated using different processes. The amount of electrolysis capacity is expected to grow significantly due to increased renewables and rising electricity demand. From a system's point of view, the location of these electrolyzers is crucial since poorly located facilities might impose further stress on the electricity and gas grids. We present a methodology to model different scenarios of the spatial allocation of electrolysis facilities. Demand-based allocation locates the facilities close to centers of future hydrogen demand, whereas generation-based allocation assigns electrolyzers to locations with high shares of renewables and negative residual load. Using an integrated electricity and gas network model, we compare five scenarios of electrolyzer allocation in the central European energy system in 2030. The results show that the spatial allocation of electrolyzers significantly impacts the optimal operation of these facilities and electricity and gas grid congestion.

2 - On the profitability of Power-to-X in energy hubs: Renewable fuels for a Greener Europe

Ioannis Kountouris, Dogan Keles

Transportation and industry are regarded as hard-to-abate sectors that necessitate a wide range of measures to reduce emissions. Renewable fuels (particularly renewable hydrogen) are viewed as viable solutions to this problem. This study conducts a techno-economic analysis of Power-to-X Hubs in Europe, optimizing yearly operations and technological investments for renewable fuel production while maximizing profits and ensuring environmental sustainability. The analysis will compare investment decisions and operation scheduling across different European regions, accounting for specific market setups and weather variability. The goal is to identify impactful factors and derives policies to incentivize financially feasible renewable fuel production, providing valuable insights into the profitability of Power-to-X Hubs within the European market while accounting for the latest EC renewable fuels delegated act.

3 - Capacity Planning for Green Hydrogen Value Chains

Tobias Cors, Malte Fliedner

Green Hydrogen generated by renewable energy sources has the potential to become a cornerstone of a sustainable energy architecture. However, given the vast investment cost and the technical difficulties of an efficient generation, storage, and supply of green Hydrogen, there is a need for modeling and solution approaches that allow for thorough economic planning of hydrogen production networks. In this work, we will present a modeling approach that captures the major economic and technical relationships of an industrial alliance comprising -among others- an offshore wind park, an electrolyzer, a cement plant, and a refinery in order to plan cost-efficient capacities of production and storage facilities. We further show how to use decomposition to incorporate the considerable uncertainties with respect to the supply of energy from renewable resources into the decision process.

■ TC-12

Thursday, 12:50-14:20 - ESA K

Electric mobility and charging profiles

Stream: Energy and Environment
Invited session
Chair: *Michael Bucksteeg*

1 - Optimization and Evaluation of Electric Vehicle Charging Profiles for Grid-Scale Network Studies using linear programming

Christoph Stockhammer

The continually increasing integration of electric vehicles will result in strain on the existing grid network. This demands advanced control strategies allowing the system operator to control the power output of each EV unit connected to the grid to meet system level objectives. In this work, we optimise and evaluate charging profiles for energy storage units to achieve both technical and economic objectives on a grid scale level. The example used reflects a reasonable scenario for how plug-in electric vehicles could be utilised for overall electrical system network benefits. An optimisation framework implemented in MATLAB is presented to reduce the grid peak load by utilising EV storage units as dispatchable assets and to minimise the electricity cost by taking advantage of the energy demand and price forecasts. We first optimise the charging profiles for a reduced-scale study involving only 20 grid-connected EVs. We show that in comparison to flat charging profiles, optimised charging profiles limit the peak grid load below the specified threshold and minimise the electricity cost significantly over the 24-hour period by selling energy back to the grid during higher energy price time intervals. We then scale up the optimisation example to a larger-scale study of 906 grid-connected EVs. To evaluate these charging profiles, an IEEE European Test Feeder is used to model the electrical distribution system. We construct the network model automatically from the network description and add a load input at each of the 2718 nodes, allowing for evaluation studies of the entire network. This illustrates that optimisation techniques and physical system simulation can reduce risk and increase profitability with early-stage techno-economic assessments of electrical power systems.

2 - Mixed-integer model to optimize electric vehicle charging pattern's environmental impacts

Leon Zacharopoulos, Nils Thonemann, Marcel Dumeier, Jutta Geldermann

The battery electric vehicle's (BEV) environmental impacts are highly influenced by the emissions attributed to the electricity used to recharge the battery. The electricity generation's environmental assessment, however, is mainly based on static yearly mean shares of primary energy sources. Further, the charging schedule is limited to the whereabouts profiles of the BEVs. To overcome this uncertainty, we develop a linear programming model to couple variable, hourly environmental impacts of electricity generation with representative user behavior in Germany. With the mixed-integer scheduling model we generate optimized charging patterns taking into consideration the BEV's environmental impact and whereabouts profile. The model is then used to quantify and optimize the mitigation potential of environmental impacts for 2019, 2025, 2030, and 2050. We aim to optimize charging behavior regarding different environmental impact categories and reveal the conflicting objectives among all the environmental categories

that arise when aiming to minimize environmental impacts holistically. Considering greenhouse gas emissions, a reduction of 38% can be achieved through optimized demand timing for 2019. This charging strategy, however, increases the depletion of material resources by 72% compared to an optimal reference charging profile. The results for the future energy generation scenarios show that deviation between environmental impact categories can deviate and differences increase over the investigated time horizon. Nevertheless, by analyzing the differences between all impact category pairs, we found six categories, including climate change, within which differences are found to be less than 10%.

3 - Allocating dynamic wireless charging technology components on airport apron road networks via branch-and-price algorithms

Stefan Helber, Imke Joormann

Many airports are trying to reduce their C02 footprint to fight global warming. One measure to this end is to electrify the fleet of vehicles operating on the airport's apron, which leads to the question of how to charge the batteries of such electric vehicles, e.g., passenger buses. As an alternative to the currently dominating conductive charging, it is conceivable to use dynamic inductive or wireless charging to transfer energy to the vehicles while they are moving on the road network through a system of underground coils that are placed at strategically chosen segments of this apron road network. In theory, this should enable vehicles with very small batteries that can be partially recharged frequently as the apron vehicles operate on a relatively small and well-defined apron road network. However, this leads to the question of how to allocate the inductive transmitter units, i.e., the coils, within the apron road network such that the required investment in the charging technology is minimized, while for a large set of conceivable vehicle service requests the required energy can be picked up on the way of handling this call. As the problem turns out to be numerically challenging, we present a branch-and-price approach using the SCIP framework to exactly solve this problem and report first numerical results based on a novel model formulation.

■ TC-13

Thursday, 12:50-14:20 - ESA W(est) 121

Recent Advances in Railway Optimization

Stream: Mobility and Traffic
Invited session
Chair: *Kanchan Joshi*

1 - Data-driven identification and quantification of influencing factors for robust planning in rail passenger transport

Janis Sebastian Neufeld, Stephan Hocke, Lisa Wesselink, Kai Heinrich, Udo Buscher

Minimizing delays is a key objective for rail network operations. At the same time, delays represent a growing challenge for rail transport companies. Current developments, such as staff shortages or bottlenecks in the infrastructure, exacerbate this. Therefore, it is essential to strive for increased robustness of circulation and duty schedules already in the planning stage. However, the effect of many methods used in practice for this purpose cannot be clearly quantified due to the multitude of reasons for disruptions and interactions in the complex traffic systems. Based on a large real-world data set with planned and actual data of German rail transport networks, we analyze influencing factors for robust planning in passenger rail transport with the help of machine learning methods. In particular, we focus on identifying factors that can be influenced in the planning process of rail transport companies. In addition to delays, we also consider the proportion of shifts and circulations that took place as planned as a target variable. Furthermore, interactions between influencing factors are also investigated across the planning stages, and properties for the classification of comparable transport networks are determined. The results can help rail transport companies to identify the measures and parameters that lead to robust planning and to evaluate plans regarding the expected reliability.

2 - Green Locomotive Assignment Problem with Data-driven Energy Consumption

Gislind Stefan, Fatih Kocatürk, Ninja Soeffker, Jan Fabian Ehmke

We investigate the Green Locomotive Assignment Problem which minimizes the total energy consumption of a heterogenous locomotive fleet over the entire planning horizon when assigning them to fixed scheduled trains. In our model, energy consumption can be reduced by allowing locomotives to be attached to scheduled trains as passive rolling stock elements and by allowing multiple locomotives to run as a consist where one active locomotive pulls the remaining locomotives. In this way, locomotives can be moved to the station where they are needed next using less energy. The energy consumption in the objective function is derived from the Davis equation, which is commonly used to calculate energy consumption in rail transport. The amount of energy required to move a train is proportional to the resistance acting on the train. The model considers the different energy consumption profiles of the different types of locomotives and the energy intensity of the track sections due to the gradient profile. In addition, the objective accounts for the regenerative energy generated during each braking operation, assuming that the different locomotive types have different capacities to generate this energy. Using information from actual train schedules, locomotive energy consumption, and actual rail line distances and gradient data, multiple linear regression models are used to predict new resistance coefficients of the Davis equation for each locomotive type. We demonstrate the potential of our model using a case study for the Austrian Railway network on problem instances generated from real-world data.

3 - A time-space network formulation to solve bi-objective locomotive scheduling problem

Kanchan Joshi, Jan Fabian Ehmke

Scheduling locomotives is a crucial railway optimization problem, especially for effective capital-intensive rolling stock planning. This paper addresses a locomotive scheduling problem that aims to assign a fleet of homogeneous locomotives located in several depot stations to pre-scheduled trains and determine a sequence of trips and empty runs to be followed by each traction unit in the fleet. The problem is represented with a time-space network formulation that provides information about the trip connections over the planning horizon and allows to manage the locomotive assignment and sequencing with consideration of empty runs based on the locomotive's availability status. By using the cyclic circulation plan restriction, we model a mixed integer linear program for two objective functions, namely, minimize the number of locomotives and minimize empty-run kilometres. The performance of the model is evaluated for both the individual objectives function as well as for the bi-objective function. In the case of the bi-objective model, a hierarchical or a weighted sum approach will be adopted to evaluate its effect on rolling stock circulation planning for the decision makers. Finally, the model is tested on real-world Austrian railway use cases to evaluate its performance for different objective functions

4 - A Strategical Train Dispatching Problem

Maik Schälicke, Karl Nachtigall

Disruptions in the operational flow of rail traffic can lead to conflicts between train movements, so that a scheduled timetable can no longer be realised. In the course of dispatching, existing conflicts are resolved and a dispatching timetable is provided. The Train Dispatching Problem now consists of selecting conflict-free train paths with minimum delay. Due to the workload of the dispatchers, the spatio-temporal observation area for dispatching is limited to one dispatching area. Up to now, conditions, such as connections or circulations, outside the dispatching area are therefore not taken into account in the dispatching decision. Therefore we introduce the Strategical Train Dispatching Problem for what a binary linear decision model is introduced. For each possible path we use a binary decision variable to indicate, whether the path is used by the train request. Such a train path is constructed from a set of predefined path parts (speed profiles) within a time-space network resulting in a large number of possible train paths, so that the column generation method is used here. Within the pricing-problem new train paths can be calculated by using shortest path techniques. Valuation of the conditions outside the dispatching area is performed using a piecewise linear cost function. Furthermore, the shadow prices of the conflict clique constraints must be taken into account, when constructing a new train path. We have to decide whether the train path belongs to a conflict clique or not. This is a very hard problem for which we present a MIP solution method. Numerical results are presented also showing the impact of the cost function for the dispatching decision.

■ TC-14

Thursday, 12:50-14:20 - ESA W(est) 120

Rolling Stock Problems

Stream: Mobility and Traffic
Invited session
Chair: *Marie Schmidt*

1 - An iterative framework for rolling stock rescheduling with railway infrastructure availability constraints

Jia Hui Zhu

Disruptions on the railway network lead to reduced availability of the railway infrastructure. In the face of such disruptions, rolling stock dispatchers are tasked with adjusting the rolling stock schedule in real-time such as to minimize the inconveniences for passengers whilst sticking as close as possible to the original plan. In this paper, we focus on developing a rolling stock rescheduling method which ensures feasibility with respect to the availability of the railway infrastructure. In particular, we research the possibility of performing shunting movements at stations where shunting is not allowed in current practice, due to the large number of trains that pass through or due to the complexity of the station layout. We introduce an iterative rolling stock rescheduling algorithm which alternates between two exact formulations, namely one that creates an interim rolling stock schedule and one that extracts the suggested shunting movements which can be performed whilst simultaneously forbidding the shunting movements which cause conflicts with other trains due to minimum headway time restrictions. We test our solution approaches with disruption instances that contain complete railway blockages throughout the Netherlands. To counter the disruptions, we allow for shunting at some of the busiest stations in the country and model the exact infrastructure of these stations to evaluate the feasibility of the suggested shunting movements. Our algorithm succeeds in adjusting the rolling stock schedule within running times of around a few minutes. We successfully identify feasible shunting movements and therefore improve upon the rolling stock schedule that would otherwise be obtained in the case that performing shunting movements at the considered stations is prohibited.

2 - Construction of a Test Library for the Rolling Stock Rotation Problem with Predictive Maintenance

Felix Prause

We describe the development of a test library for the rolling stock rotation problem with predictive maintenance (RSRP-PdM). Our approach involves the utilization of genuine timetables from a private German railroad company. The generated instances incorporate different probability distributions functions for modeling the health states of the vehicles. Additionally, the considered trips possess varying degradation functions.

RSRP-PdM involves assigning trips to a fleet of vehicles and scheduling their maintenance based on their individual health states. The goal is minimizing the total costs consisting of operational costs and the expected costs associated with vehicle failures.

The failure probability is dependent on the health states of the vehicles, which are assumed to be random variables distributed by a family of probability distributions. Each distribution is represented by the parameters characterizing it, which get altered whenever a trip is operated. We incorporate both linear and non-linear degradation functions to describe the inference of the parameters.

The variety of instances is augmented by the variability of the operational lifespan of the vehicles and by considering the timetables of the individual lines isolated or in groups, particularly when they involve similar types of vehicles.

Overall, we employ these assumptions and utilize open source data to create a library of instances with varying difficulty levels. Our approach is vital for evaluating and comparing algorithms designed to solve the RSRP-PdM.

3 - Robust rolling stock rescheduling

Marie Schmidt, Joris Wagenaar, Evelien van der Hurk, Richard Lusby

After a disruption has occurred, railway operators have to reschedule timetable and rolling stock schedule to keep operations on the undisrupted network running as smooth as possible. However, at the start of the disruption, it is hard to make exact predictions on when exactly it will be resolved. In this presentation, we present two different approaches to rolling stock rescheduling anticipate that the disruption may take longer than initially hoped. We compare these approaches against each other and against the 'optimistic' approach that reschedules for the predicted disruption duration.

4 - Delay Management on a Path

Sven Jäger

In delay management the primary question is whether or not connecting vehicles will wait for delayed arrivals. The goal is to minimize the passenger's total arrival delay. While the general problem is NP-hard, several polynomially solvable special cases have been identified, which raises the question of determining the exact precise complexity boundary. In this context, it has been shown that in the case where passengers from potentially delayed feeders want to board a single trip at different stations, the problem can be solved in polynomial time by a dynamic program if the connecting trip has no slack times, while it is NP-hard if slack times are allowed (Gatto et al., 2004; Gatto et al., 2005). We consider the similar case, where the network is a single path consisting of multiple vehicle trips connected by transfer arcs. The delays occur on the driving arcs on this path. We present a dynamic program that solves this case in polynomial time, regardless of whether the driving or transfer arcs have slack, thus making a new contribution to the determination of the complexity boundary for delay management. We complement this result with some initial insights about the online variant of the problem, where the delays only become known over time.

■ TC-15

Thursday, 12:50-14:20 - R 0077, VMP5

Emergency Services

Stream: Health Care Management
Invited session
Chair: *Melanie Reuter-Oppermann*

1 - Triage of injured persons at mass casualty incidents with algorithms and/or drones

Franziska B. Metz, Melanie Reuter-Oppermann

Traffic accidents, terrorist attacks or natural disasters regularly lead to mass casualty incidents (MCI), which significantly exceed the supply capacities of the rescue service. In order to ensure the survival of as many patients as possible, it is particularly important to classify the injured persons according to urgency of treatment. Various algorithms are available for this triage. These algorithms suggest a sequence of defined questions and processes (e.g. checking vital signs), at the end of which each patient is assigned to one of these triage categories. Thereby a fast and reliable identification of vital threatened persons is crucial in order to treat them as quickly as possible. The aim of the work is to analyse and compare triage done by paramedics with common triage algorithms and triage done by drones with e.g. imaging techniques and thermal cameras. These techniques should be used to detect the number of injured patients, their vital signs, injuries, body temperature etc. to use for triage algorithms or direct for a classification to triage categories. In the future, a simulation will be used to analyse the time required and the accuracy of patient classification.

2 - Multi-Modal Patient Transportation and Allocation Strategies during Mass-Casualty Incidents: A Simulation-Based Evaluation of Policies.

Florentina Hager, Melanie Reuter-Oppermann

Among the primary goals during mass-casualty events is to provide fast medical care to the affected individuals. With a high number of casualties, this leads to a complex task. In the past, several research papers proposed different mathematical models as well as heuristics to optimise patient transportation and allocation. However, with time being a crucial factor, on-field decisions are typically based on practical and straightforward policies, such as sending casualties to the closest hospital until the capacity limit is reached. Therefore, this study seeks to develop and evaluate different patient transportation and allocation policies during mass-casualty incidents using discrete event simulation. A distinguishing feature of this study is the differentiation between vital and severely injured casualties. While vital injured casualties must be transported directly to a medical centre, severely injured patients are considered to be stable enough to be transported using alternative modes of transportation, freeing up ambulances for

other patients and decreasing overall transportation times. To evaluate the effectiveness of various policies, multiple scenarios are developed and tested.

3 - Machine learning-based patient selection in an emergency department
Melanie Reuter-Oppermann, Nikolaus Furian, Michael O'Sullivan, Cameron Walker

The performance of Emergency Departments (EDs) is of great importance for any health care system, as they serve as the entry point for many patients. However, among other factors, the variability of acuity levels and corresponding treatment requirements of patients visiting EDs imposes significant challenges on decision makers. Balancing waiting times of patients to be first seen by a physician with the overall length-of-stay over all acuity levels is crucial to maintain an acceptable level of operational performance for all patients. To address those requirements when assigning idle resources to patients, several methods have been proposed, including the Accumulated Priority Queuing (APQ) method. The APQ method selects patients based on linearly assigned priority scores to patients with respect to their time in the system and acuity level. This paper investigates the potential of a Machine Learning (ML) based patient selection method. It assumes that for a large set of training data (near) optimal assignments can be computed by a (heuristic) optimizer and aims to imitate such optimal behavior when applied to new situations. Thereby, it incorporates a comprehensive state representation of the system and a complex non-linear selection function. The motivation for the proposed approach is that high quality selection decisions may depend on a variety of factors describing the current state of the ED, not limited to waiting times, which can be captured and utilized by the ML model. Results show that the proposed method significantly outperforms the APQ method for a majority of settings.

■ TC-16

Thursday, 12:50-14:20 - R 0079, VMP5

Parallel Computing

Stream: Software for OR
Invited session
Chair: *Yuji Shinano*

1 - Pushing the Limits of Computation: Solving previously unsolvable instances
Yuji Shinano

We have developed the Ubiquity Generator framework (UG), which is a software framework to parallelize state-of-the-art solvers on large-scale computing environments, for more than 10 years. The parallel solvers instantiated by the UG successfully solved more than 20 previously unsolved instances from MIPLIB(benchmark instances for Mixed Integer Programing), 5 instances from SteinLib (benchmark instances for Steiner Tree Problems), and 3 instances from QAPLIB (benchmark instances for Quadratic Assignment Problems). In this talk, we present the latest status of UG and parallel solvers instantiated by the UG.

2 - A Parallel Benders' decomposition approach for the transshipment vehicle routing problem
Junko Hosoda, Stephen Maher, Yuji Shinano

A supply chain management problem that integrates the determination of consolidation locations with the coordination of long-haul and local vehicle routing is a complicated problem. The parallel and Benders' decomposition approach is used to solve this problem. The lower bound is computed by solving the relaxed model with decomposition and the upper bound is computed using the heuristic algorithm. The relaxed solver and heuristic solvers compute in parallel. The effectiveness of the parallel and decomposition approaches is discussed in the presentation.

3 - Faster than any Quantum Computer: On the state of QUBO solving
Thorsten Koch, Daniel Rehfeldt, Yuji Shinano

It is regularly claimed that quantum computers will bring breakthrough progress in solving challenging combinatorial optimization problems relevant in practice. In particular, Quadratic Unconstraint Binary Optimization (QUBO) problems are said to be the model of choice for use in (adiabatic) quantum systems during the NISQ era. Even the first commercial quantum-based systems are advertised to solve such problems. QUBO is an interesting way of modeling combinatorial optimization problems. Theoretically, any Mixed Integer Program can be converted into a QUBO. In practice, however, there are some caveats. Furthermore, even for problems that can be nicely modeled as a QUBO, this might not be the most effective way to solve them. We review the state of QUBO solving on digital and Quantum computers and give insights regarding current benchmark instances and modeling. Finally, we present results from comparing the performance of these systems with state-of-the-art parallel software on classical digital computers.

■ TC-17

Thursday, 12:50-14:20 - ESA O(st) 121

Column Generation

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Maria Baier*

1 - Deep Chebyshev center-based column generation
Maria Baier, Dirk Lebiedz

Chebyshev center-based column generation is a gently stabilized variant of classical column generation that uses dual information provided by interior points instead of extremal ones in order to identify improving columns. From a dual perspective, the basic algorithm corresponds to the well-known Chebyshev center cutting plane method, which draws on weak dual bounds and converges still rather slow in practice. We present deep Chebyshev center-based column generation, a sophistication operating on stronger bounds and employing deeper (dual) cuts. Besides giving first numerical evidence of its superiority over both classical and state-of-the-art Chebyshev center-based column generation, we provide some interesting analytical insights that can be exploited in the realm of column generation and beyond.

2 - Fastening column-and-constraint-generation algorithms with column generation
Henri Lefebvre, Martin Schmidt, Johannes Thürauf

Column-and-constraint-generation (CCG) algorithms are among the most popular approaches for solving adjustable robust problems. In the recent years, they have been successfully applied to a variety of problems, most of which have continuous wait-and-see decisions. While it is typically acknowledged that CCG can scale relatively well for problems with continuous wait-and-see decisions, the same cannot be claimed for problems in which (mixed-)integer decisions must be taken after the uncertainty is revealed.

In this talk, we computationally evaluate the performance of CCG algorithms when applied to problems with mixed-integer second-stage decisions and discuss its main weaknesses. Then, we show how column-generation techniques can be employed to alleviate these burdens and successfully reduce the computational time needed to prove optimality. Additionally, we also introduce a new heuristic method, which is based on the column-generation procedure to quickly find feasible solutions at each step of the CCG. The scheme can also be enhanced with domain-specific knowledge on the deterministic version of the problem being solved and can exploit parallelism. Finally, we also highlight that the method can, at each iteration, be warm-started by knowledge gained at previous iterations of the CCG. This is in contrast to standard CCG algorithms where each iteration solves a new problem from scratch.

The computational benefits of the proposed scheme is then evaluated on two optimization problems arising in logistics and energy system planning.

3 - A large-scale real-world approach for CREW SCHEDULING
Hsuan-Pin Wu, Alexander Souza, Denys Trieskunov

We consider the CREW SCHEDULING problem, where tasks have to be organized into shifts, while respecting labor rules and geographic and temporal consistency. It is an NP-hard optimization problem with substantial literature.

We contribute a novel formulation of the problem, which trades runtime for memory. It is based on MIN COST FLOW with additional constraints on edge-sets. The underlying network can become quite large. This drawback is compensated with these advantages: The formulation can be treated with column generation, where the number of pricing subproblems is large, but each one requires only a shortest path computation (to be solved in linear time). Since the subproblems are independent, they can be solved in parallel. The restricted master LP - a SET COVER type problem - links the subproblems with the aforementioned constraints and grows at most linearly with the number of solutions of the subproblems.

We have implemented the algorithm and have enhanced it substantially gaining a large speed-up. Firstly, the do not create the large network upfront. Instead, we generate it on the fly and create only the vertices and edges that are actually needed by the column generation. Secondly, we have trained an ML model supporting the master-iteration to decide which subproblems to be solved next. Hence a large number of evaluations of subproblems are avoided. Thirdly, we implemented the pricing to be executed on cloud or local instances. By cloud-enablement, we are able to scale to an arbitrary number of subproblems while avoiding that the runtime also scales accordingly.

A preliminary implementation of the algorithm is already in productive use at a large Swiss railway company. Thus our work has proved to be useful in a real-world application, too.

4 - Applying Column Generation for the Fixed Route Dial a Ride Problem
Hagai Ilani, *Elad Shufan*, *Tal Grinshpoun*, *Aviad Zlotnick*, *Oksana Sabinik Pecherski*

Fixed Route Dial-a-Ride Problem (FRDARP) is a version of the known Dial-a-ride problem. It can be used as a transportation solution for several scenarios, for example scheduling shuttles between airports and hotels. The goal is to set the transportation of passengers between fixed terminals along a predetermined route while minimizing the gap between the passenger's requested time, either for pick-up or delivery, and the actual arrival time of the transport. A solution should determine the partition of passengers into shared transports and the departure time of the transports using a known vehicle fleet. By a reduction to the shortest path problem, we previously showed that the problem is polynomial in the number of requests, but with a high degree polynomial. To solve FRDARP optimally, past solutions used dynamic programming as well as integer programming. In this study, we propose a new approach based on column generation. We demonstrate that the obtained subproblem is that of interval scheduling, which can be efficiently solved by a reduction to the minimum cost flow problem. The runtime of our approach is competitive with other methods and, in many cases, outperforms them. Our experiments indicate that we consistently obtain integer solutions without resorting to branch and price. If the linear programming relaxation solutions are always integral, then the FRDARP can be one of the few examples where column generation competes with the simplex method. On the applicative side, the column generation method may offer a promising alternative for solving FRDARP.

■ TC-18

Thursday, 12:50-14:20 - ESA O(st) 122

Discrete Optimization Solution Algorithms II

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *John Warwicker*

1 - Support Vector Machines within a Bivariate Mixed-Integer Linear Programming Framework
John Warwicker, *Steffen Rebennack*

Support vector machines (SVMs) are a powerful machine learning paradigm, performing supervised learning for classification and regression analysis. A number of SVM models in the literature have made use of advances in mixed-integer linear programming (MILP) techniques in order to perform this task efficiently. In this talk, we present three new models for SVMs that make use of piecewise linear (PWL) functions. This allows effective separation of data points where a simple linear SVM model may not be sufficient. The models we present make use of binary variables to assign data points to SVM segments, and hence fit within a recently presented framework for machine learning MILP models. Alongside presenting an inbuilt feature selection operator, we show that the models can benefit from robust inbuilt outlier detection. Experimental results show when each of the presented models is effective, and we present guidelines on which of the models are preferable in different scenarios.

2 - Reusable Benders cuts for bi-objective mixed integer linear programming
Duleabom An, *Chungmok Lee*, *Sophie Parragh*

We investigate bi-objective mixed integer linear programming problems to which Benders decomposition can be applied. Benders decomposition is a widely used technique for exploiting problem structures that arise in real-world applications, including supply chain network design problems. Typically, the Benders master problem concerns the strategic decisions such as the facility location decisions while the Benders subproblem deals with the operational decisions, such as commodity flow. Our study focuses on a sustainable supply chain network design problem that aims to minimise both economic and environmental objectives. To address the two objective nature of the problem, we employ the weighted-sum method. The following issue then is that we repeatedly have to solve similar problems with different weight values. To tackle this, we propose a simple way to reuse the generated Benders cuts in subsequent iterations of the weighted sum method. The underlying idea is that if the weights are similar, the Benders master problem would not require too many new Benders cuts to be generated, enabling us to start the Benders decomposition for the master problem with some pre-generated Benders cuts. This work is supported by Austrian Science Fund (FWF): P 31366, P 32954.

3 - A novel cut selection strategy for Benders Decomposition
Florian Rösel, *Lukas Glomb*, *Frauke Liers*

Benders Decomposition (BD) has been used to solve a variety of optimization problems. The performance of BD is strongly influenced by the choice of the cuts to be added during the course of the algorithm.

Several algorithmic approaches to make this choice are known. The so-called Magnanti-Wong method aims for Pareto-optimal Benders cuts. Cuts based on minimal infeasible subsystems of a modified version of the Benders sub problem have proven to provide strong cuts. Recently, methods using facets of the sub problem's value function's epigraph as Benders cuts have been developed.

We contribute to the field of cut selection strategies for BD by developing a new notion of Pareto-optimality, that incorporates, in contrast to the Magnanti-Wong notion of Pareto-optimality, the behavior of the cuts on the whole feasible domain of the Benders master problem. We prove that cuts that are non-dominated according to our notion are non-dominated in the sense of Magnanti-Wong as well. We provide an approach to calculate non-dominated cuts according to our notion, that solves a single linear program that has one variable and one constraint more than the standard dual Benders sub problem.

We benchmark our cut selection strategy against the other known strategies on various instances. Some instances are taken from the MIPLib, others are multi-commodity flow network design problems, and others are randomly generated MIPs. The computational results show, that a hybrid selection strategy consisting of minimal infeasible system cuts and our cut selection strategy is the most efficient in terms of running time. Further, the results show, that our cut selection strategy is the most efficient measured in the number of Benders cuts that are needed to solve a problem.

■ TC-19

Thursday, 12:50-14:20 - ESA O(st) 123

Robust Optimization II

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Marc Goerigk*

1 - Robust optimization with belief functions
Marc Goerigk, Romain Guillaume, Adam Kasperski, Pawel Zielinski

We consider optimization problems with an uncertain objective function, where the uncertainty is specified by providing a discrete scenario set. In an alternative setting to classic distributionally robust approaches, the concept of belief functions in the traditional and possibilistic setting is applied to define a set of admissible probability distributions over the scenario set. The generalized Hurwicz criterion is then used to compute a solution. The complexity of the resulting problem is explored, and some exact and approximation methods of solving it are proposed.

2 - Solving the recoverable robust shortest path problem in DAGs
Pawel Zielinski, Marcel Jackiewicz, Adam Kasperski

Recoverable robust shortest path problem (Rob Rec SP) in directed acyclic multigraphs under the interval uncertainty representation is investigated. In the Rob Rec SP, we are given: the first-stage arc costs, which are precisely known, the set of possible realizations of uncertain second-stage arc costs, represented by the Cartesian product of interval costs, and a recovery parameter. A decision process in the Rob Rec SP is 2-stage and consists in finding a path in the first stage. Then in the second stage (the recovery stage), after a cost scenario reveals, the first stage path can be modified by choosing a path under the revealed cost scenario from its neighborhood depending on the recovery parameter (a limited recovery action is allowed). The goal is to find a path that minimizes the sum of the first stage cost and the recovery cost in the worst case (over the set of cost scenarios). The Rob Rec SP problem is strongly NP-hard and not approximable unless P=NP in general digraphs and polynomially solvable in arc series-parallel multigraphs (Busing, 2012).

In this paper, we give polynomial time algorithms for the Rob Rec SP in layered multigraphs and in general directed acyclic multigraphs. We also show a complete polynomial time algorithm for Rob Rec SP in arc series-parallel multigraphs; in Busing, 2012, only an idea of an algorithm is given. Thus, the above results fill a gap in the computational complexity of the Rob Rec SP problem.

3 - Robust Network Design for Nonlinear Flows
Johannes Thürauf, Julia Grübel, Martin Schmidt

We consider the problem of designing a network to transport nonlinear and potential-based flows with demand uncertainties. More precisely, we use robust optimization to compute a network design that admits a feasible transport for all, possibly infinitely many, demand scenarios within a given uncertainty set. To this end, we show that a given network design is robust feasible, i.e., it admits a feasible transport for all demand uncertainties, if and only if a finite number of special scenarios can be routed through the network. We compute these special scenarios by solving nonlinear and continuous optimization problems. Embedding this result for robust feasibility in an adversarial approach then leads to an algorithm that computes a robust network design in a finite number of steps. Since all of our results are valid for general (i.e., nonlinear) potential-based flows, we can apply the approach to gas, hydrogen, or water networks to obtain a network design that is robust feasible and cost optimal. Finally, we demonstrate the applicability of the method using gas networks with infinitely many demand scenarios.

■ TC-20

Thursday, 12:50-14:20 - ESA W(est) 119

Behavioral insights on AI-based decision support

Stream: Game Theory and Behavioral Management Science
Invited session
Chair: *Florian E. Sachs*

1 - Explanations in AI-based Decision-Support: The Role of Task Complexity and Cognitive Ability
Monika Westphal, Michael Vössing, Gerhard Satzger, Galit Yom-Tov, Anat Rafaeli

The capabilities of artificial intelligence (AI) are continuously increasing. This raises questions about the willingness of users to trust and rely on AI-based decision-support (AI-based DS). We study how users perceive and to what extent they comply with AI-based DS, when they receive an explanation. Recent literature shows that providing explanations does not always yield the desired outcomes. These inconclusive findings likely occur because of influencing factors that have not yet been considered. In this work, we consider task complexity and users' cognitive abilities. In three experimental studies, we recruited 548 participants on Prolific and let them (in the role of hotel managers) determine hotel room prices. Based on data from over 40.000 hotels on booking.com, we trained an AI using XGBoost and neural networks. Participants encountered the same (of determining room prices) task again, but this time received AI-based DS and an explanation. They decided whether they wanted to update their initial estimations (for the room prices), based on this new information. In the end of the study, participants indicated their perceptions of trust and understanding, and their intention to comply with the AI-based DS. We find that providing explanations leads users to experience the task itself as more complex, which hampers their perceptions of and compliance with the AI-based DS. Users only benefit from provided explanations when they have high cognitive abilities. With the continually increasing complexity of work environments, this work has clear implications for organizations, and especially for integrating AI-based DS into the workplace.

2 - Towards Effective Human-AI Collaboration: The Role of Human Learning in Appropriate Reliance on AI Advice
Max Schemmer

The true potential of human-AI collaboration lies in exploiting the complementary capabilities of human and AI to achieve performance superior to that of the individual AI or human, i.e., to achieve Complementary Team Performance (CTP). To realize this complementarity potential, humans need to exert discretion in following an AI's advice, i.e., they need to rely on the AI's advice appropriately. Previous work has focused on building a mental model of the AI to distinguish whether an AI recommendation is correct or incorrect. However, recent research has shown that the mental model alone cannot explain appropriate reliance. We hypothesize that, in addition to the mental model, human learning is a key driver of appropriate reliance and thus CTP. In this study, we demonstrate the relationship between learning and appropriate reliance in an experiment with 100 participants. This work provides fundamental concepts for the analysis of reliance behavior and derives implications for the effective design of human-AI collaboration.

3 - Algorithm aversion at first sight: Insights on people's tendency to eschew algorithm-based decisions
Florian E. Sachs, Dmitri Bershadskyy, Kai Heinrich

As digitalization progresses, an increasing number of human decisions can be substituted or aided by corresponding algorithms, which often exhibit superior performance compared to humans. Nevertheless, despite knowing that the algorithm can outperform humans, users tend to avoid its utilization, a phenomenon referred to as algorithm aversion. Prior research has identified numerous potential factors attributed to human, machine, or task properties, yet the influence of the initial human-computer interaction remains to be elucidated. Given that attitudes towards the algorithm develop gradually and are susceptible to change during interactions, manipulating the interaction and measuring reactions can aid in understanding potential strategies to mitigate aversion and encourage appreciation. In order to explain possible reasons for algorithm aversion or appreciation, we conduct an incentivized online experiment that centers on the impact of the sequence in which information regarding the quality of the algorithmic system is presented.

■ TC-21

Thursday, 12:50-14:20 - ESA W(est) 122

Optimization in Modern Official Statistics

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Ulf Friedrich*

1 - Synthetic populations and microsimulations at the service of decision makers and official statistics

Morgane Dumont

Synthetic populations aim to create populations in a micro level, that fit data available at different aggregation levels. This requires processes optimising the fit between available data and the resulting population. The determination of the individual attributes corresponds to a discrete optimisation, whereas the grouping of the individual into coherent households can be performed with combination optimisation techniques. In demography or transport, their use is frequent, but many other domains suffer from a lack of data at the individual level and could benefit from the use of the same methods. Official statistics also sometimes employ synthetic population techniques to join different databases. Moreover, synthetic populations are often necessary as input to microsimulations, performing modelling (and forecasts) at the microlevel and allowing the implementation of a multitude of scenarios at different levels of aggregation. This paper will first briefly introduce the different concepts and example uses in decision making. Then, two different applications that have been implemented will be presented. The first one concerns a project called "Virtual Belgium In Health", a platform containing a microsimulation with different submodels (birth, ageing, death, marriages, divorce, moves) with the aim of applying health and care scenarios. To illustrate the huge possible range of applications, the second one presented considers the simulation of space debris in geostationary orbit, combining a deterministic model with synthetic populations techniques.

2 - Computational solution of large household allocation problems

Lucas Moschen, Ulf Friedrich, Ralf Münnich, Martin Schmidt

Microsimulation models are powerful tools that have become increasingly important when evaluating the effects of societal changes as for example in the health sector, the economy, or the social policy. A dynamic spatial microsimulation model of Germany is currently being developed in the research project MikroSim. Here, an important aspect of the modelling process on the municipal level is the allocation of households to specific dwellings at given geographic coordinates.

This work elaborates several aspects of the household-dwelling allocation problem. In particular, we show how given information on the household and dwelling data sets can be incorporated to improve the statistical quality of the proposed allocation. Our model yields a hard combinatorial optimization problem which is generally too large to be solved directly with standard Branch&Bound-solvers. We present a solution algorithm that combines a decomposition of the original problem and a penalty approach for some of the constraints. The novel algorithm is able to solve large problem instances and a numerical study shows that the overall quality of the computed allocation is high.

3 - Fair and stable school districting

Ulf Friedrich

The shapes and sizes of municipal school districts have a major impact on the lives of a large part of the population. Of course, school districts affect the quality of eduction directly, but there are vast implications for families beyond that, e.g., safety considerations, the choice of employment or the need of car. It is clear that, on the one hand, the school districting process needs to be fair and comprehensible. On the other hand, the financial, political, and infrastructural situation of cities imposes a framework of constraints to the process. We discuss school districting under two main aspects: the fairness of the districts and their stability over a time horizon of several years. Both objectives are combined in a mixed-integer programming model for school districting under a flexible set of constraints. We show how the choices of policy makers affect several variables, among them the walking distances for students, class sizes, and school way safety. To keep school districts stable over time, the model incorporates past data and simulations for future years. Finally, we assess the model under external stress, e.g., by industrial relocation or major changes in school policies.

■ TC-23

Thursday, 12:50-14:20 - ESA W(est) 222

Flexibility and Resilience

Stream: OR in Engineering
Invited session
Chair: *Florian Roland Breda*

1 - What are the Limits of Deterministic Planning in Uncertain Environments?

Florian Roland Breda

We explore the consequences of deterministic planning within an uncertain environment, focusing on the trade-offs between best-case and worst-case scenarios. We investigate how the performance of systems modeled using Mixed Integer Programming (MIP) - considered as ideal systems (best-case) - can be impacted by uncertainties and less-than-ideal parameters. Our starting point is the crane scheduling problem, a widely studied problem in operations research. We create two simplified models for 2D instances. A deterministic model and a robust model that incorporates uncertainty. The Manhattan distance traveled is used as a measurement criterion for the success of the movement strategy. We compare the outcomes of the robust and the deterministic model and assess the cost of deterministic planning - i.e., how expensive it is to assume the best-case scenario in the tested instances. Furthermore, we investigate how bad the parameters in a model need to be before the idealized assumptions break down and the deterministic model's performance deteriorates.

2 - Achieving Optimal Truss Topologies using Mathematical Optimization

Julian Mrochen

We propose a novel method for designing and optimizing truss-like structures using mathematical optimization. As additive manufacturing continues to advance, innovative structural design methods become increasingly relevant in practical applications. To this end, we present an approach that combines established truss optimization techniques in engineering with technical operations research methods. The model developed is capable of optimizing truss structures while accounting for the effects of moving structural elements under various loading scenarios. The primary objective is to quantify the advantages of dynamic structures over rigid ones in terms of efficiency and effectiveness as well as demonstrate that mathematical optimization is a compelling tool for advanced applications in structural engineering.

3 - Market-based Control of Fluid Systems

Tobias Constantin Meck, Kevin Logan, Peter Pelz

Pump-valve systems are at the core of many processes throughout industry and the private sector and account for a large share of their total energy consumption. Additionally, these systems need to be resilient against changing load demands, wear of components or even component failures. Control problems - like setting the rotational speed of the pumps or the valve positions - can be solved Pareto-optimally by mathematical programming if the load profile is known and a precise mathematical model of the system can be derived. However, for the real time control of complex processes, both the load profile as well as the system behaviour is often uncertain. This leads to alternative control solutions that deviate from the global optimum. We propose a multi-agent approach that is based on the free market principle. Here, a software agent is assigned to each active component (i.e., pumps and valves). The corresponding agent has access to the measurement data of the component (e.g., pressure difference), can adjust its set-points (i.e., rotational speed or valve position) and possesses a virtual budget. The agents trade volume flow guarantees and thereby try to maximise their own profit. Through the individual profit maximation, the system-wide goal of low energy consumption and high fulfilment rates of specified demands is sought to be achieved. We compare the proposed method with the global optimal solution for the control of a simple model of a booster station for high-rise buildings. Although global optimality cannot be achieved, the results are promising and outperform conventional control methods by a large margin.

4 - The single row facility layout problem with chance constraints

Louisa Schroeder, Anja Fischer

In the single row facility layout problem (SRFLP) machines are arranged in a plant floor along one side of a path without overlapping. The aim is to minimize the handling costs of the material, which are represented as the sum of the pairwise distances between the machines weighted with the costs of the material flow. The majority of the literature assumes complete knowledge of the input data for the SRFLP. In real life scenarios the input data is unknown beforehand and the predictions may underlie fluctuations. Therefore, it is reasonable to take uncertainty of the input data into account. In this talk we present a new version of the SRFLP by using chance constraints to consider variations in the material flow between the machines. We assume that the material flow follows a multivariate normal distribution. We present preliminary results.

■ TC-24

Thursday, 12:50-14:20 - ESA O(st) 120

Theory and practice

Stream: Project Management and Scheduling
Invited session
Chair: *Marjan van den Akker*

1 - Improved hybrid local search algorithm for the Continuous Energy-Constrained Scheduling Problem with step-wise cost function

Roel Brouwer, Marjan van den Akker, Han Hoogeveen

We consider a variant of the Continuous Energy-Constrained Scheduling Problem (CECSP), introduced by Nattaf et al. (2014). A set of jobs has to be processed on a continuous resource. Each job requires a given total amount of resource during its execution. We want to find a schedule such that: a job does not start before its release time, is completed before its deadline, and respects its lower and upper bounds on resource consumption during processing. Our objective is to minimize a piece-wise constant increasing function of the completion time. We look at the case where both the resource and time are continuous. We assume that there is no efficiency function influencing resource consumption. We present a hybrid local search algorithm that exploits a decomposition of the problem, where we use local search to find an order of events (start/completion of a job, step in a cost function), and for a given order determine optimal start and completion times as well as resource consumption using an event-based LP formulation. We accelerate the search by approximating the objective function, especially the penalty terms, in the initial stages of the search. We extract information from solutions that helps us identify promising directions for the search. We perform computational experiments to compare the performance of our algorithm with exact approaches and to show its ability to deal with larger problem sizes. Our approach can be extended to deal with explicit precedence relations and linear efficiency functions.

2 - Order acceptance and scheduling in capacitated job shops

Florian Linß, Mike Hewitt, Janis Sebastian Neufeld, Udo Buscher

Order acceptance and scheduling in capacitated job shops We consider a capacitated job shop problem with order acceptance. This research is motivated by the management of a research and development project pipeline for a company in the agricultural industry whose success depends on regularly releasing new and innovative products. This setting leads to multiple problem characteristics not commonly considered in scheduling problems. Each job has a given release and due date and requires the execution of an individual sequence of operations (job shop). The execution of each operation requires processing on a different machine for a known period of time. There is a set of machines of fixed capacity, each of which can process multiple operations simultaneously. Given that typically only a small percentage of jobs yield a commercially viable product, the number of potential jobs to schedule is on the order of several thousand. Due to the limited capacity, not all jobs can be started. Instead, the objective is to maximize the throughput. Namely, to start as many jobs as possible. We present a Mixed Integer Programming (MIP) formulation of this problem and study how resource capacity and the option to delay jobs can impact research and development throughput. We show that the MIP formulation can prove optimality even for very large instances with less restrictive capacity constraints, while instances with a tight capacity are more challenging to solve.

3 - Scheduling position-dependent maintenance operations in single machine layouts

Andreas Hipp

Even though machines' wear and tear typically occur in real-world production environments, it has not been sufficiently treated in traditional machine scheduling for a long time. In scheduling research since the 1980s, time-dependent deterioration is usually identified as the main factor for machine wear and tear. In our work, we focus on machine deterioration not influenced by time, but by the number of jobs. Every job, regardless of its processing time, leads to the same deterioration, which is tantamount to position-dependent deterioration or maintenance (introduced by Drozdowski et al. in 2017). After a given number of jobs, the machine is completely worn and must be restored by processing a maintenance operation of fixed length. This maintenance operation can also be processed earlier, which leads to the same effect for the machine - being totally restored. A special case of this constraint is assuming fixed positions for the maintenance operations in the final job sequence. Position-dependent (pd) maintenance in general is relevant in every real-world setting, in which the number of jobs causes the main deterioration and not their length, like the wear and tear of batteries of automobiles with combustion engines or the landing gear of aircrafts. So far, only a few studies have tackled scheduling problems with pd maintenance yet. In this work, we therefore study single machine problems dealing with pd maintenance regarding their runtime complexity and present solution approaches to solve the appropriate layout.

4 - Robustness Measures For Stochastic Parallel Machine Scheduling

Marjan van den Akker, Loriana Pascual, Roel van den Broek, Han Hoogeveen

We consider the stochastic parallel machine scheduling problem with precedence constraints, release dates and an overall deadline for the complete schedule. To deal with uncertainty in the job processing times, it is desirable to create robust schedules. Because parallel machine scheduling problems are NP-hard, they are often solved with local search methods.To include robustness into the objective of a local search approach, an efficient way to quantify the robustness of a solution is required. Exact computation of the robustness of a schedule can be done simulation. However, this is computationally expensive when it has to be performed in every iteration of the local search. Therefore, the need for surrogate robustness measures arises.

In an elaborate computational study, we evaluated several existing robustness measures, together with a measure that we proposed ourselves, on their ability to estimate the true robustness, with the aim of creating stable baseline schedules bounded by a deadline. We compared the values of the robustness measures with the results of a Monte Carlo simulation by reporting their Spearman's rank correlation coefficients for various notions of robustness and several processing time probability distributions. Furthermore, we implemented a local search algorithm which uses the robustness measures as objective function. We showed the effectiveness of robustness measures as indicators of true robustness and their practical application in generating stable baseline schedules.

■ TC-25

Thursday, 12:50-14:20 - ESA O(st) 222

Dynamic Pricing

Stream: Pricing and Revenue Management
Invited session
Chair: *Claudius Steinhardt*

1 - Dynamic Pricing for Shared Mobility-on-Demand Systems with Differentiated Fulfillment Options

David Fleckenstein, Fabian Anzenhofer, Robert Klein, Claudius Steinhardt

Shared mobility-on-demand (SMOD) systems are becoming increasingly popular as a complement for line-based transportation in cities and a replacement in rural areas. Generally, the aim is to make public transport more economically efficient and more attractive to customers, thereby increasing their willingness to forego owning private cars. Hence, SMOD systems must be similarly reliable as line-based public transport and offer rides tailored to the customers' individual preferences. To achieve this, providers can define differentiated, dynamically priced fulfillment options that allow customers to, e.g., place requests with a guaranteed offer, requests for express rides, and advance requests. In this talk, we present a post-decision rollout algorithm for solving the resulting integrated demand management and vehicle routing problem. We show that our solution approach provides an anticipatory opportunity cost estimate including both marginal cost-to-serve and displacement cost and considering the impact of future pricing decisions. Using real-world data from a rural SMOD provider, we assess the impact of dynamic pricing with differentiated fulfillment options on the system performance regarding multiple objectives such as economic efficiency, reliability, and sustainability.

2 - Selling empty seats: Dynamic pricing of ancillary services

Davina Hartmann, Siqi He, Christiane Barz, Jochen Gönsch

Over the past 25 years, revenue management has developed into an established area of research, and most transportation companies are implementing some form of dynamic pricing or capacity control. However, the pricing of ancillary services such as reservations or extra space is a relatively new area. We present a novel dynamic programming formulation for a transportation company that sells tickets in the same compartment in various ways: 1) without a seat reservation (i.e., customers are guaranteed a seat, but they cannot choose if it is, e.g., an aisle or window seat), 2) tickets with a seat reservation, and 3) tickets with a seat reservation and extra space (i.e., a guaranteed empty seat next to their reservation). We suggest different solution methods to solve this problem efficiently in practice and discuss the upper bounds of the dynamic program. Our results will be illustrated in numerical examples.

3 - Envy-free dynamic pricing schemes

Julian Golak, Kristof Berczi, Laura Codazzi, Alexander Grigoriev

A combinatorial market consists of a set of indivisible items and a set of agents, each agent having a valuation function over the subsets of items. The goal is usually to determine a pair of pricing and allocation of the items that provides an efficient distribution of the resources, or is as profitable as possible for the seller. A recent line of research has concentrated on dynamic pricing schemes where agents arrive in an unspecified sequential order, and the prices can be updated between two agent-arrivals. It was shown that the dynamic setting is capable of maximizing social welfare without the need for a central coordinator. However, this approach has an implication on the fairness of the final allocation that is usually not emphasized. The model assumes that the customers' sole objective is to pick a bundle of items maximizing their utility with respect to the prices available at their arrival, and they are not concerned with prices at earlier and/or later times. This means that the final allocation together with the prices at which the items were bought do not necessarily form an envy-free solution over all time horizon. We study the existence of optimal dynamic prices under fairness constraints in unit-demand markets. We propose four possible notions of envy-freeness depending on the time period over which agents compare themselves to others: the entire time horizon, only the past, only the future, or only the present. For social welfare maximization, we give polynomial-time algorithms that always find envy-free optimal dynamic prices in the latter three cases. For revenue maximization, we show that the corresponding problems are APX-hard if the ordering of the agents is fixed, but are tractable when the seller can choose the order

4 - Dynamic Pricing with Target Revenue

Rouven Schur, Jochen Gönsch

In this presentation, we explore the application of dynamic pricing in fields where firms do not encounter a high number of sales process repetitions. Unlike traditional dynamic pricing models that focus on maximizing expected revenue, we address the unique challenges faced by firms operating in such fields. These firms, burdened by high fixed costs, often do not feel comfortable with maximizing expected revenues. Instead, they might prioritize achieving a predefined target revenue.

We introduce a dynamic pricing model that incorporates the concept of target revenue as a key component in the optimization process. By integrating this target revenue into our model, decision-makers gain the flexibility to prioritize reaching their revenue goals while still considering expected revenues. This alternative perspective opens up new avenues for decision-making in these specific fields of application.

The presentation includes the demonstration of the structural properties of the optimal solution and the value function within our dynamic pricing model. Additionally, we share preliminary results of a short numerical study. These results offer a glimpse into the potential impact and effectiveness of incorporating target revenue considerations into the dynamic pricing process.

Thursday, 14:35-15:35

■ TD-01

Thursday, 14:35-15:35 - ESA A

Plenary talk Kemme

Stream: PC Stream
Plenary session
Chair: *Wolfgang Brüggemann*

1 - Out of the Box Thinking - Real Life OR Applications for Container Terminals

Nils Kemme

Container terminals are critical interfaces between waterside and landside transport in globalized supply chains and are as such of significant importance for global trade and welfare. The efficient design and operation of container terminals require many strategical, tactical, and operational decisions. Against this background, several hundred research papers from the field of operations research have dealt with a multitude of relevant planning problems of container terminals over the past two decades and proposed innovative approaches to solving them. In practice, hardly any of these approaches are applied. In this work, it is therefore focused on real-world planning and solution methods at container terminals. For selected planning problems, it is critically reviewed why scientific methods are rarely applied in practice, which approaches are typically used at terminals around the globe, and which OR methods, including machine learning, are successfully applied by some innovative terminals.

Thursday, 15:50-17:20

■ TE-02

Thursday, 15:50-17:20 - ESA B

Advanced Decision-Making Methods and Applications

Stream: Decision Analysis and Support
Invited session
Chair: *Andreas Rudi*

1 - Development of a Two-Stage Stochastic Optimization Model for Humanitarian Supply Chain
Sonia Alikhah, Mehdi Sharifyazdi, Andreas Rudi

Natural and man-made disasters can cause catastrophic consequences, including increased mortality, immigration, property and income loss, public dissatisfaction, and significant environmental damage. To mitigate the effects of disasters, appropriate measures must be taken before and after an event to provide affected populations with essentials such as food, water, clothing, shelter, and medical care. This paper formulates a facility location optimization model for the case of Berlin to carry out effective and cost-efficient pre- and post-disaster planning and relief operations by designing a relief goods distribution network. The facility location model involves allocating facilities to serve a widely spread population, based on different scenarios for locating and distributing relief goods.The paper has employed a two-stage stochastic programming (TSSP) approach which is particularly useful in the context of humanitarian disaster management, as it allows for the modeling of both uncertainties and time-dependent decisions, considering the private sector's uncertain response and varying demand levels.The model focuses on minimizing social costs, which include both logistics and deprivation costs. Deprivation costs represent human suffering due to lack of access to goods or services and should be minimized from a social perspective. The first stage of the model considers scenarios and assumptions to determine optimal locations, distribution center capacities, and prioritization for opening and closing of the facilities. In the second stage, decisions involve delivering and prepositioning relief items from warehouses on the outskirts of Berlin, transporting goods to distribution centers, satisfying demand, and ensuring timely delivery.

2 - Using Inverse Optimization to Discover Sustainability Priorities in Purchasing Decisions
Florian Kellner, Sebastian Utz

Among researchers, politicians, private sector decision-makers, and throughout the population, there is growing awareness of the urgent need for the transition towards a sustainable economy. Research shows that buying firms have substantial leverage to initiate sustainable development by controlling the sustainable performance of their suppliers. Thus, integrating sustainability in the supplier evaluation and selection process is attracting increasing attention in research and practice. This research presents a novel methodology based on inverse optimization to derive the implicit, actual preferences of decision-makers in the trade-off between traditional sourcing objectives and sustainability in the supplier selection and order allocation process. One advantage of using implicit preferences, among other advantages, is that they are derived from real-world decision situations, that is, they are measured after the decision has been made and, thus, do not suffer from self-reporting biases. The derived purchasing priorities can then be used for further analyses to gain a better understanding of the characteristics of the purchasing managers and sourcing situations that come with particularly high/low priorities placed on sustainability. Since the inverse optimization approach is computationally resource-intensive and consumes a significant amount of time, we present a scalable state-of-the-art cloud architecture that allows solving an arbitrary number of optimization programs in an acceptable amount of time. We demonstrate the feasibility of the proposed methodology in a real-world case. In doing so, we test how important sustainability aspects are in the supplier selection and order allocation decisions of one of the world's largest automotive parts manufacturers.

3 - A Framework for Data-Driven Explainable Optimization
Michael Hartisch, Kevin-Martin Aigner, Marc Goerigk, Frauke Liers, Arthur Miehlich

In recent years, explainability has become a major research area in machine learning, but in the field of operations research and mathematical programming, the comprehensibility of solutions has often been overlooked. However, users and subjects of the optimization model that are not familiar with mathematical programming, are in need of easily comprehensible explanations in order to gain and maintain trust in the optimization process. In this work, we present a data-driven framework that provides simple certificates for solutions of optimization problems. By using similarities in instance and solution features, we leverage historic data to generate explanations that a solution must be good because in a very similar situation a very similar solution was implemented. Using a shortest path setting, we experimentally validate our framework and show that the price of explainability can be small. Overall, our framework offers a valuable tool for enhancing the comprehensibility of solutions in mathematical programming, making them more accessible and trustworthy to a wider audience.

4 - Designing a Self-Sufficient Urban Renewable Energy System: A Multi-Objective Optimization Approach
Constanza Eslava-Hurtado, Felipe Díaz-Alvarado

The energy transition is posing diverse challenges worldwide. At present, green hydrogen is considered a potential solution. However, its production is projected mainly through large-scale facilities in remote locations. This study proposes that cities leverage their renewable energy potential to generate power to meet their needs and transition to energy self-sufficiency. This transition can be supported by decision-making models, as presented herein. The model provides the optimal location and sizing of small-scale power generation facilities, including solar panels on roofs, wind turbines in urban corridors, electrolyzers for hydrogen production, and batteries as an alternative for energy storage. A case study is presented to illustrate the use of the model on a municipal scale. The problem is formulated as a Multi-Objective Optimization (MOO) model, addressing economic cost and environmental impact as objective functions. Environmental impacts are quantified by ReCiPe 2016 taken from the EcoInvent database. A goal programming approach is adopted for the MOO formulation. This formulation takes the form of a Mixed-Integer Nonlinear Program (MINLP). The result of the model shows the optimal location and size of the facilities to generate electricity from the urban renewable energy potential and meet the demand for the study case. This model is proposed as a decision-making tool with a scientific basis for transitioning to a self-sufficient urban renewable energy system.

■ TE-03

Thursday, 15:50-17:20 - WiWi A, VMP5

Integrated and Robust Models for Planning and Scheduling: A Look at Ports and Farming Operations

Stream: Logistics
Invited session
Chair: *Jens Frische*

1 - Robust models for strategic first-mile capacity planning under uncertainty
Jens Frische, Arne Strauss

We consider a strategic first-mile logistics challenge of planning transport capacities in collaboration with a carrier collecting parcels from businesses on a fixed schedule with time windows. Our research project examines a key question for strategic first-mile routing decisions under uncertainty.

The decision maker must select the appropriate capacity (the supply side of the equilibrium), which is fixed before all demand and network information is available. Deciding the capacity levels bears the risk of inefficiency from high capacity costs (if the level is set too pessimistic) or failure to serve customers (if the capacity is set too optimistic). We explore the suitability of robust vehicle routing models for real-world scenarios, considering the uncertainties inherent (e.g., demand fluctuation) or exogenous (e.g., longer travel times due to congestion) to such operations.

Our main contribution is the empirical validation of a recent robust vehicle routing problem (robust CVRPTW) in real-world applications to obtain more efficient routing plans while being resilient against unfavorable materializations of uncertain factors.

2 - Multi-objective optimization for planning cultivation and harvesting operations in the sugarcane industry

Teresa Melo, Angelo Aliano Filho, Washington Oliveira

We address a problem arising in the sugarcane production chain that concerns the integrated planning of cultivation and harvesting operations. For this purpose, we develop a mixed-integer nonlinear programming model to decide on the different sugarcane varieties to be grown on a given set of plots, the periods for their cultivation, the subsequent harvesting periods, and the type of harvesting equipment to be deployed. These decisions are subject to various constraints related to matching harvest periods with cultivation periods according to the maturity cycles of the selected sugarcane varieties, the availability of the harvesting machinery, the expected demand for sucrose and fiber, and other technical requirements. Three conflicting objectives are considered, namely maximizing the total amount of sucrose and fiber produced, minimizing the total time devoted to harvesting, and minimizing the total cost of moving the harvesting equipment. We use linearization techniques to obtain a computationally tractable formulation, which is solved by a tailored exact method based on the augmented Chebyshev scalarization method. The latter is extended with a mechanism to identify an initial feasible integer solution that proves to be very useful by reducing the computational effort required to obtain Pareto-optimal solutions. A computational study is conducted on a set of semi-randomly generated instances that reflect current cultivation and harvesting practices in Brazil. The numerical results obtained demonstrate the effectiveness of the proposed methodology and allow an in-depth analysis of the trade-offs between the three competing objectives, thereby facilitating the decision-making process.

3 - Electric Vehicle Routing with Lunch Breaks

Fabian Brockmann

The Electric Vehicle Routing Planning (EVRP) is a challenging problem that requires finding the optimal route for electric vehicles to travel, while considering factors such as battery capacity, charging infrastructure, and time constraints. This paper addresses the EVRP problem with forced driving pauses, as stated in the EU regulation No 561/2006. The traditional approach to incorporate these pauses is to first solve a model formulation that neglects the forced pauses and then repair the obtained routes by fixing required pauses within the routes. In contrast, this paper proposes an approach that incorporates the pauses directly in the optimization model as constraints. The aim is to understand whether it matters to incorporate these pauses by the traditional approach, and to identify which features differ in the so obtained solutions. We conduct experiments on randomly generated instances to explore the impact of incorporating pauses in the EVRP. The findings indicate that this approach can result in a considerable reduction of overall driving time and total costs.

■ TE-04

Thursday, 15:50-17:20 - WiWi B1, VMP5

Mastering Optimization in Logistics: Customer Choice, Scheduling, and Inbound Logistics

Stream: Logistics
Invited session
Chair: *Epaminondas Kyriakidis*

1 - Optimal choice of next customer in stochastic single vehicle routing problems with pick-up and delivery

Epaminondas Kyriakidis, Theodosis Dimitrakos, Andreas Papasalouros

We consider a vehicle routing problem in which a single vehicle starts its route from a depot and visits N customers in order to deliver to them new products and to collect expired products. The customers are not serviced according to a predefined sequence. The demands of the customers are assumed to be discrete random variables with known distributions. Actual demands become known only when the vehicle visits them. The vehicle may interrupt its route and go to the depot in order to unload the expired products and to restock with new products. The cost structure includes travel costs between customers and travel costs between each customer and the depot. After the first visit at each customer's site two decisions must be made. The first decision is to choose the next customer that the vehicle will visit. The second decision is to choose how the vehicle will go to the next customer. The problem is to find (i) the minimum total expected cost for servicing all customers and (ii) the optimal decisions that must be made after the first visit at each customer's site. The above problem can be solved by implementing a suitable stochastic dynamic programming algorithm.

2 - Solving Hybrid VRP with time windows

Taicir Loukil

Amira Belhaj Ammar Taicir Loukil Mohamed Cheikh University of Sfax MODILS,TORS

For a long time, reducing the overall cost of transportation was a big issue for businesses that improve. As a result, one of the most researched combinatorial optimization issues is the vehicle routing problem. A considerable technological change to human existence, particularly in the area of transportation, offers several benefits in terms of time, safety, and comfort. The environment suffers greatly. Therefore, some governments require logistic corporations to incorporate new environmental limitations and objectives for vehicle routing difficulties in order to acquire both commercial and environmentally beneficial solutions, which raised the Green VRP concept. Erdogan & Miller-Hooks (2012) considered the Green VRP as a progression of the conventional VRP. The Hybrid VRP, that Mancini (2017) described it as a new variation of the traditional VRP, adheres to the same goals as the green vehicle routing problem. Because hybrid vehicles utilize hybrid energy sources, they can get around the issue of a lack of charging stations for electric vehicles. Mancini's analysis did not include the time window constraints. This constraint was therefore intended to be included in the mathematical formulation. In this study we consider the hybrid vehicle routing problem with time window (HVRP-TW) that is a variant or an extension of the Vehicle Routing Problem with time window, one of the core problems in combinatorial optimization. Our work will be divided into two main sections, on the first hand we will propose a model with time window constraint and develop a heuristic that solves large instances of HVRP-TW. Finally we will test the heurisitcs'effectiveness

3 - Optimizing inbound logistics in the automotive industry

Ingmar Steinzen, Jens Peter Kempkes, Stefan Bunte, Dominik Hollmann

Large production plants have hundreds of suppliers with volumes ranging from multiple trucks per day to a few parcels per week. Often, trucks arrive half-empty at plants which results in inefficient transports. Manually identifying cost-optimal transport modes and schedules is very time-consuming or even impossible for planners. Thus, logistics costs are higher than they need to be and the interdependences of changes are not transparent. We show how we support freight planners in the optimization of freight flows with a decision support system based on the Optano technology platform. The optimization methodology improves the efficiency of the logistical processes and achieves sustainable cost savings. We show results from the automotive industry.

4 - Optimal Scheduling in Classification Yards with Train Processing Options

Henning Preis, Daniel Haalboom, Nikola Besinovic

Classification yards are important nodes in railroad networks, especially in the single-wagonload transport system. The operations are complex due to a high number of involved resources and restrictive dependencies. Decisions on job sequencing and resource allocation have a major impact on outbound delays and thus on the quality of service in the network. Due to permanent updates of arrival times and resource availabilities, a constant revision of the schedules is necessary. This also includes decisions on alternative processes to speed up the processing of delayed trains. In some cases it is useful to deviate from the standard treatment by replacing certain processes, parallelize activities or assigning additional personnel. The paper addresses these options and their integration into a comprehensive scheduling approach. Therefore, a Mixed-Integer-Program considering train processing options is presented together with the data preparation. It includes all necessary types of resources, i.e. tracks, personnel and locomtives together with their interdependencies and time constraints. The objective function minimizes the overall outbound delay. Afterwards, some practical scenarios adapted from the classification yard in Munich operated by DB Cargo AG are calculated with CPLEX. The results of the optimization approach are presented and evaluated regarding to the effects of the alternative train treatments. Finally, conclusions are derived for operating the model in real-time-environments of classification yards.

■ TE-06

Thursday, 15:50-17:20 - ESA C

Supply chain coordination

Stream: Supply Chain Management
Invited session
Chair: *Sandra Transchel*

1 - Trends and Shortcomings in Closed-Loop Supply Chain Coordination Research: a Systematic Literature Review

Nazanin Nami, Grigory Pishchulov, Joao Quariguasi Frota Net

Closed-loop supply chains (CLSCs) are regarded as a key approach to mitigating environmental depletion and pollution. Such systems require collaboration among several parties with different perspectives and interests that are not always well-aligned. Supply chain coordination mechanisms offer a tool to consider all parties' interests and optimise overall supply-chain performance. In recent years, a growing body of literature on CLSC coordination has emerged, yet it lacks an up-to-date and comprehensive review. To this end, this study conducts a framework-development systematic literature review on CLSC coordination. Major elements of our proposed framework are internal factors, external factors, CLSC modelling approach, and coordination. We focus on exploring the effects of coordination in CLSCs, identifying the shortcomings of the existing studies, and providing insights for scholars and future research directions. Some significant identified limitations in the CLSC coordination area include a lack of complex CLSC designs and empirical research to represent real-world problems, limited-option agreements and short-term perspectives, insufficient attention to social and environmental aspects, lack of consistency in CLSC coordination terminology, and limited attention to customer behaviour and cultural and technological challenges.

2 - Optimal Long-term Procurement Contracts with Risk-Averse Suppliers

Mohsen Elhafsi, Mohammad Zolghadr

We investigate the dynamics of a long-term contract between a manufacturer who procures a crucial component from an upstream risk-averse supplier, considering the supplier's holding and backorder costs. The supplier privately knows his inventory position, and the manufacturer provides incentives to extract the supplier's private information. We use direct mechanism design within a Markov Decision process framework to characterize the optimal contract and derive the first order optimality conditions of the contract. We show that our contract resolves a dynamic three-way interaction: Extracting the supplier's private information, exploiting the supplier's inventory carryover, and optimizing the channel surplus. (i) To extract the supplier's private information, the manufacturer uses a "deferred payment" strategy. (ii) Based on the supplier's inventory position reporting, the manufacturer adjusts her order to exploit the supplier's inventory carryover effect. (iii) And finally, the manufacturer optimizes channel surplus by internalizing the vertical externalities and intertemporal externalities. One of our interesting findings is that as the risk-aversion degree of the supplier becomes sufficiently large, the second-best optimal contract converges to its first-best counterpart. Indeed, as the supplier's risk aversion degree increases, the monetary compensation of procurement from all suppliers with different inventory positions, increases to the point that the manufacturer becomes indifferent to the inventory position of the supplier and considers the whole population of suppliers as homogeneous. In other words, increasing the suppliers' risk aversion degree narrows the distribution of suppliers over their inventory positions.

3 - Measuring Supply Chain Resilience in the Automotive Value Chain - A comparative research on literature and industry perspective

Sophia Raaymann, Stefan Spinler

In this research the authors investigate how supply chain resilience (SCR) can be measured in companies along the automotive value chain. About three years after the start of the COVID-19 pandemic disrupting global supply chains, companies increasingly focus on creating supply chains resilient towards the next disruption. While researchers have developed multiple frameworks and quantitative models on how to assess risk in supply chains, the question of how to measure resilience with operative KPIs on a regular basis remains unanswered. Accordingly, this research strives to answer how SCR can be measured in the automotive industry. To do so, researchers investigate literature's perspective through text mining on 198 published papers on SCR and compare that to the industry's perspective. The method applied on text mining results is the Analytical Hierarchy Process helping to find the most suitable combination of KPIs. For the industry data, a conjoint method was applied in interviews, of which's results were analyzed by an ordinal regression. The research reveals that the most important KPIs according to literature are the variation of lead time, the OTIF and the volume flexibility negotiated with suppliers, while the industry assigns the greatest contribution towards resilience to the schedule adherence of the customer, followed by the stock level of high-risk parts and the volume flexibility of the supplier. Additionally, OEMs, Tier1 and Tier2 suppliers have different priorities among the top 3 KPIs. Accordingly, perceptions of how to measure resilience vary within the industry as well as between industry and academia, implying a greater need of exchange between industry and academia as well as a more structural discussion of resilience KPIs within the industry.

4 - The impact of different contracting mechanisms on the performance of reusable packaging systems

Sandra Transchel

The development of reusable packaging systems for food products is becoming increasingly important to decrease the consumption of virgin materials, packaging waste, and the risk of rising raw material prices. Implementing functioning reusable packaging systems that guarantee a smooth circulation of the reusables is, however, quite challenging and requires the collaboration and coordination of various stakeholders in a supply chain (e.g., collection, cleaning, transport, and managing deposits).

We investigate the impact of different contractual agreements in a two-stage supply chain on the effectiveness of reusable packaging systems with a deposit system. We particularly study a supply chain consisting of two producers using reusable packaging for their products, and a wholesaler who sells the products as an intermediary to the retailers. Besides the product price, the wholesaler must pay a deposit fee for each reusable package to the producer, which she gets back when she sells it to the retailer (forward flow). Once consumers have consumed the product, they may return the package to the retailer, who must pay back the deposit. The wholesaler picks them up from the retailer, sorts the different packages as well as possible, and sends them back to the producer to be reused. Sorting, however, is cost-intensive and the wholesaler may have limited incentive to invest too much effort in sorting. At the same time, producers have limited incentives to invest in higher return rates, as they may benefit from forgone deposits. We develop a game-theoretical model that studies different types of contracts and their impact on the performance of the reuse system along different dimensions.

■ TE-07

Thursday, 15:50-17:20 - ESA J

Decision Support for Financial Planning and Analysis

Stream: Decision Analysis and Support
Invited session
Chair: *Sebastian Utz*
Chair: *Florian Kellner*

1 - Mean-Variance-Climate Risk-efficient portfolios

Sebastian Utz, Ralph E. Steuer

This paper investigates the financial performance of portfolios generated by a new model that simultaneously optimizes risk, returns, and climate risk in an empirical study. We address the question of whether the portfolios generated by the suggested model are feasible, i.e., the portfolios generate a reasonable financial performance and have less climate risk. To test the feasibility of the portfolios, we conduct an empirical study based on a sample of S&P500 constituents in the period from 2005 to 2020. A firm is only considered in the portfolio tool in a month in which it was also included in the S&P500. To estimate the financial indicators for these firms, we downloaded the return time series from Bloomberg. For the climate risk measure, we follow recent literature on climate finance and use total carbon intensity from Trucost. Total carbon intensity is measured as the ratio of tons of carbon

emissions over million USD revenues. The overall findings show that the integrated portfolio model generates portfolios that show substantially lower climate risk and financial out-of-sample performance that is not significantly lower than currently available portfolios.

2 - How Artificial Attention shapes Human Intention

Rene Schallner, Carolin Kaiser, Vladimir Manewitsch

Robo-advisors are making waves in finance as new digital asset management tools. But despite the significant market growth, some investors remain skeptical, which might be attributed to the fact that currently, most robo-advisors are text-based websites. With the rise of social robots as service providers, it is crucial to understand if making virtual finance advisors more human-like increases investors' trust. We explore how their human-like appearance and behavior, like eye contact, affect consumer trust and investment decisions. In an online experiment, ca. 4500 participants consulted with a financial advisor: either a human or a robot with different levels of human-likeness and eye contact, or a textual advisor. Speaking segments of an actress and the social robot "Furhat" as financial advisors were recorded and merged into a virtual advisory dialogue. Participants chose the amount to invest and if they wanted their funds managed by a human or a machine, followed by a questionnaire about their attitudes. We found robotic advisors are trusted less than humans but lead to significantly higher satisfaction and likelihood of choosing the machine-managed asset than text-based advisors. Eye contact significantly increased trust, liking, satisfaction, and recommendation likelihood of human and even robotic advisors. We conclude human-like robotic advisors perform significantly better than textual ones and demonstrate the beneficial effects of eye contact, even in robotic advisors. Thus, helping creators of advisory offerings to provide better service with increased trust and customer satisfaction. We raise awareness that consumers are more likely to trust and follow advice if an advisor has human-like features, adding to discussions about the role of AI in society.

3 - Persuasive channel choices - evidence from manager-investor interactions

Anthony Haake, Wolfgang Breuer, Bertram Steininger

This study develops and evaluates a model for an optimal channel mix for persuasive communication. Suppose different disclosure channels induce different processing costs and a listener's processing capacity for information is constrained. In that case, a persuader benefits from distributing positive and negative information differently to maximize the listener's understanding of the positive and to minimize it for the negative information. By doing so, a persuader effectively increases her persuasive power. We show that our linear model predicts actual channel choices made by real-world persuaders in the setting of earnings announcements with an out-of-sample approach. Although our model only considers the information's tone and readability, it predicts up to 69 % of channel choices correctly which is statistically significant. We provide robustness tests by assessing the sensitivity of the model's predictive power to changes in numerical assumptions. Additional analysis indicate that persuasive channel choices are a selfish act as these are predominantly done by firms with low ESG scores and high institutional ownership. A critical discussion of our results and an outlook for future research is provided.

4 - Dynamic Team Rating for Sports

Kei Takahashi

This Study proposes a method for dynamic team rating in league sports. Massey and Colley's method is a team rating method based on wins, losses, and goal difference.These methods are actually used in college basketball and baseball. However, when these methods are dynamically applied to league sports, the system breaks down, especially in the case of long leagues with interruptions, interruptions due to championship leagues, rainouts, or no games due to scheduling conflicts. This study proposes a method to overcome this drawback. We define several desirable properties of a rating system and show that the proposed method satisfies them. Finally, we compare the methods by applying them to actual league sports data and predicting wins and losses through simple logistic regression using only ratings as explanatory variables.

■ TE-09

Thursday, 15:50-17:20 - ESA O(st) 221

Nonsmooth Optimization

Stream: Continuous and Global Optimization
Invited session
Chair: *Mario Jelitte*

1 - An asynchronous proximal bundle method

Frank Fischer

Proximal bundle methods are well-known algorithms to solve nonsmooth convex optimization problems. The basic idea is to iteratively compute new candidate points by solving a cutting plane model of the function and to evaluate the function at a new point. If the progress in the function value is good enough, the algorithm goes to the candidate point, otherwise the cutting plane model is improved.

We extend the classic iterative method into a fully asynchronous algorithm. This means that all function evaluations as well as solving the cutting plane model is done in parallel and may take arbitrary time. The results of all processes arrive over time and are combined to achieve global progress. This approach has several advantages over the classic approach, e.g. multiple different cutting plane models may be used to compute several candidates and multiple processes may evaluate the same functions at different candidate points at the same time.

We show that the algorithm converges under mild assumptions and can be used as a drop-in replacement for the classic sequential approach, i.e. no additional information besides a first-order oracle for the function evaluation is required. In particular, we show how the algorithm learns important structural properties of the functions to control the inaccuracy induced by the asynchronicity automatically such that overall convergence can be guaranteed. We also present first numerical experiments for solving large scale models for facility layout problems.

2 - Mixed-integer nonlinear robust optimization via nonsmooth methods

Martina Kuchlbauer

Currently, there are few approaches available for general nonlinear robust optimization, which typically require restrictive assumptions on the adversarial problem or do not guarantee robust protection. We present an algorithm that combines outer approximation and a bundle method and which is applicable to convex mixed-integer nonlinear robust optimization problems requiring only inexact worst-case evaluations. In particular, our method does not rely on a specific structure of the adversarial problem and allows it to be nonconvex. As robust protection requires a global solution of the adversarial problem, it is a main challenge in such a general nonlinear setting. Our method requires these evaluations only up to a certain precision. For example, approximating a nonconvex adversarial problem via piecewise linearization and solving the resulting problem up to any requested error, the required assumptions are met.

We model a robust optimization problem by a nonsmooth mixed-integer nonlinear problem and tackle it by an outer approximation approach that requires only inexact function values and subgradients. For the arising nonlinear subproblems, we present an adaptive bundle method. We prove its convergence to approximate critical points and, as a consequence, finite convergence of the outer approximation approach.

As an application, we study the gas transport problem under uncertainties on realistic instances and provide computational results showing the efficiency of the method.

3 - Sufficient Conditions for Lipschitzian Error Bounds for Complementarity Systems

Mario Jelitte

We are concerned with Lipschitzian error bounds and Lipschitzian stability properties for solutions of a complementarity system. For this purpose, we deal with nonsmooth slack-variable reformulations of the complementarity system, and study conditions under which the reformulation serves as a local error bound for the solution set of the complementarity system. We also discuss conditions, guaranteeing metric regularity of the reformulation mapping, and investigate relations between the latter, and Lipschitzian stability properties for solutions of the complementarity system. The talk is based on a joint work with A. Fischer and A.F. Izmailov.

■ TE-10

Thursday, 15:50-17:20 - ESA W(est) 221

Assortment Planning

Stream: Choice Based Analytics
Invited session
Chair: *Friederike Paetz*

1 - Distribution-specific approximation guarantees for the random parameters logit assortment problem

Stefan Rogosinski, Sven Müller, Kevin Djoenneady Poetera

This presentation is about the random parameters logit (mixed logit) assortment problem and approximations based on the revenue-ordered assortment where we order the products by their revenue and a product can only be offered when all products with higher revenue are also offered. Under this condition the runtime becomes polynomial instead of exponential. We now want to find out how good this approximation is and we want to find an approximation factor and upper bounds for this factor and how this depends on the distribution of the customers utility function random parameters.

2 - Product Line Design vs. Assortment Optimization under the Mixed Multinomial Logit Model

Niloufar Sadeghi, Oliver Vetter, Cornelia Schoen

The problem to find the most profitable product line under customer choice behavior has been separately addressed in the Product Line Design (PLD) as well as in the Assortment Optimization (AO) literature. The AO problem under Mixed Multinomial Logit (MMNL) is NP-hard. Existing exact methods for AO problem are computationally inefficient when applied to real-world instances of larger size and these instances can only be tackled with heuristic methods. We study exact solution procedures as well as approximation schemes and other heuristic methods for the PLD and the AO problem with discrete pricing under the MMNL demand model. We contribute to the existing literature in the following ways: (i) We review the current PLD and AO literature stream under the MMNL model, link the two streams that have largely been treated separately so far, and discuss conditions when the PLD and the AO problem formulations are equivalent such that their solution results in the same product line. (ii) We improve the Conic approach by adopting valid constraints from literature and applying a branch and cut technique and our computational tests show that this enhancement solves our problem instances on average between 35% - 66% faster. (iii) We show that a Fully Polynomial Time Approximation Scheme (FTPAS) algorithm exists for the AO problem even if the discrete pricing decision is included. (iv) We test in a numerical performance analysis of solution quality and time, whether solving the AO problem formulation is advantageous over solving the equivalent PLD problem formulation with state-of-the-art methods, or vice versa. This also includes a newly developed hybrid approach that theoretically combines the advantages.

3 - Predictive Error Bounds for the Mixed Logit Model for the Random Parameters Assortment Problem

Kevin Djoenneady Poetera, Stefan Rogosinski, Sven Müller, Knut Haase

Assortment optimization problems are revenue-maximizing problems, which involve the selection of a subset of products to be offered to customers. We present the assortment optimization problem under the mixed logit model demand (MXL). To reduce the computational effort in the sample average approximation process due to large samples, we discuss multiple variance reduction techniques for this problem. We derive theoretical bounds of the predictive errors from each variance reduction method and compare them with the errors from traditional pseudo-random numbers to determine their impact on the optimization process. In particular, we investigate the relationships between model formulations (Mixed Integer Programming and Mixed Integer Non-Linear Programming), variance reduction techniques (i.e., generation and the number of draws), and computational effort required.

4 - Conjoint analysis on charging tariffs for EVs

Dustin Sperling, Richard Woeste, Peter Letmathe

Electric vehicles are becoming increasingly popular. As the number of electric vehicles increase, so do the requirements for a reliable charging infrastructure. Current implementations do not always meet these complex requirements. For example, an average of 18% of public charging operations in Germany currently fail. In the EMoT research project, a test center is being designed to address this issue. In the course of this, user preferences for charging tariffs are investigated. A particular focus is on the value that is attached to the accessibility to reliable charging infrastructure. This question is answered by a choice experiment. Different tariff features are weighed against each other so that a corresponding end customer benefit can be determined for different levels of the tariff features. The choice experiment is used to determine which tariff features are of particular interest, what value is attached to the reliability of charging infrastructure and whether customers are able to find the most favorable tariff for them.

■ TE-11

Thursday, 15:50-17:20 - ESA H

Teaching OR for Sustainability

Stream: Energy and Environment
Invited session
Chair: *Jutta Geldermann*
Chair: *Isabel Wiemer*

1 - Teaching Operations Research for Energy System Research: Challenges and Real-Life Examples

Sophie Pathe, Leonie Sara Plaga, Christine Nowak, David Huckebrink, Valentin Bertsch

We explore the challenges of teaching OR for sustainability assessment, using real-life examples from three case studies in the field of energy system research. The first case study examines the influence of different flexibility options on the German electricity system in 2045. Students learn to use a linear programming national electricity system model for optimal investment and scheduling decisions, compare results of different scenarios, and use sensitivity analysis to test the sensitivity of a solution against uncertain input data. The second case study focuses on exploring possibilities for decarbonizing households' energy demands. Students learn about the methods of energy system optimization, comprehend the influence of input data on the optimized results of a household energy system model, and analyze and compare investment and scheduling results of different input data. The third case study involves a life cycle assessment of a wind turbine, which includes aspects of multi-criteria decision making. Students learn about life cycle assessment, different weighting methods, and basics of structured decision making. These case studies will be made publicly available as part of the research project "Operations Research (OR) for Sustainability: Energy, Mobility, Industry". We also address students' views on the case studies based on evaluation results and specific surveys. Initial results of the evaluation show that students particularly appreciated that they learned to analyze and interpret results comprehensively as well as the realistic approach of the first case study. Considering this, we particularly discuss benefits and challenges of using real research results and data for teaching.

2 - Challenges of Uploading Case Studies as Open Educational Resources for Teaching Operations Research for Sustainability

Isabel Wiemer, Erik Pohl, Jutta Geldermann

For teaching a wide range of Operations Research (OR) methods, gaining a deep understanding and applying real-world examples, case studies are frequently used. In this context, Open Educational Resources (OER) have been gaining lots of attention in recent years. However, OER is still provided in an insufficient way. One main reason might be the multiple challenges regarding the uploading process. To address this issue, we develop a digital, model- and application-oriented teaching/learning program named "Operations Research for Sustainability: Energy, Mobility, Industry". Current research projects for the design and evaluation of sustainable energy, mobility and industrial systems are prepared as case studies. In a first step, the case studies are provided as Moodle-courses including descriptions, learning videos and online-tests. Afterwards, the elaborated Moodle-courses are uploaded as high quality OER on a free online portal for digitally supported teaching and learning at universities. Within the project, one of the elaborated case studies deals with energy efficiency in container terminals. We discuss early lessons learned of the case study's preparation, implementation and evaluation process in Moodle. Additionally, we point out the most important requirements during the uploading process to provide the case study as OER material. Thus, we foster a culture of collaboration and knowledge-sharing within the academic community.

3 - Teaching an OR sustainability case study with complex data on different academic levels: challenges and solutions

Stephan Bogs, *Johanna Ruett*, *Grit Walther*

As teaching OR focuses often on abstract methods, powerful OR applications opportunities with their significance for practice are often not conveyed to students. While there are some didactic case studies in production and logistics, they often lack a sustainable perspective. However, excellently trained staff will be needed to tackle the huge sustainability challenges of our time. Against this background, the objective of this presentation is to present the didactic treatment of a real-world sustainability case study with complex data with specific focus on teaching on different academic levels (bachelor and master). The core of the case study is the design of supply networks to produce renewable fuels, e.g. for aviation or shipping, as a current planning problem with practical relevance. For solving this problem, model requirements, data, OR model and results are available on a European scale. We present a concept of how we have transformed this practical case study into a didactic case study. We teach our case study as a bachelor and a master level online course. Adapting the didactics to both levels entailed various challenges. A particular challenge is to teach the students how to incorporate many different data sources into their model. We start from a small data base in Germany, and show the iterative development of the model from a one-stage single objective WLP to a two-stage, two-objective model. Finally, we extend the data to cover the whole EU. We also teach the respective software implementation. At the end, the students can develop a model independently, even for a practical case, implement it in software and thus also master the transfer to other tasks.

4 - Application of portfolio theory to optimize power plant mixes and challenges of programming in Python

Qinghan Yu, *Barbara Glensk*, *Reinhard Madlener*

The ongoing rapid changes in the energy sector are the reason why decision-makers require more sophisticated optimization methods supporting their investment and operational decisions under risk and uncertainty. In recent years, it has become increasingly popular to take financial risk considerations explicitly into account when deciding about long-term investments in large-scale power supply systems. Sensitivity analysis including risk assessment in electricity generation planning, however, typically does not incorporate portfolio risk and thus cannot replicate the profit-risk or cost-risk relationships. In this context, it makes sense to adopt techniques from finance theory, such as the mean-variance portfolio approach, which allows investors to create low risk and high return portfolios under various - e.g. economic, technical and social - criteria. This situation opens also for students' new possibilities to learn how the real business problems can be solved with methods from finance and operation research applied to the energy domain. In the case study offered, the students are offered to learn the basics of mean-variance portfolio theory, the economics of selected power plants, and how to apply the theory to optimize power plant portfolios. In the context of real assets, the main challenge is to define the rate of return as a portfolio selection criterion and to simulate it in the modeling. The analysis is conducted by using the object-oriented programming language Python, which creates some specific challenges that are discussed in the case study as well.

■ TE-12

Thursday, 15:50-17:20 - ESA K

Decentralized energy systems

Stream: Energy and Environment
Invited session
Chair: *Jannis Eichenberg*

1 - Design and control of household energy systems considering photovoltaic systems, lithium-ion battery as well as hydrogen storage, and demand side management

Simon Sassen, *Andreas Fink*

Abstract: New technologies in power and heat generation are one way to escape the rising costs of conventional energy. However, there are many different power and heat generators based on renewable energy sources, all of which differ in their fixed and variable costs. Therefore, we study heuristic and exact optimization approaches for the design and control of household energy systems in the context of current technological developments and societal/environmental goals. We consider multi-level decision problems arising from the combination of intermittent energy sources, expensive storage systems (lithium-ion battery, hydrogen storage) with related technology choices, and operating modes taking into account typical energy load profiles with the possibility to schedule certain demands. We mainly consider total annualized cost as the objective function and describe the problems as MILP models. Depending on the complexity of the problem, exact solvers are combined with heuristic methods to determine appropriate solutions. The computational results illustrate typical solutions depending on the considered scenarios.

2 - Adaptive Energy Management System for Multi-Architecture Microgrids using Curiosity-Driven Deep Reinforcement Learning

Mohamed Saâd El Harrab, *Michel Nakhla*

Microgrids, integrating renewable sources and storage systems, offer reliable, secure, cost-effective power. The rise of distributed energy resources and complex energy management demands efficient microgrid optimization.

Machine learning, particularly Deep Reinforcement Learning (DRL), addresses microgrid optimization challenges. DRL agents learn optimal control policies through trial and error, suitable for complex problems. DRL algorithms and advanced optimization techniques develop innovative Energy Management Systems (EMS) to optimize energy generation, consumption, and storage, enhancing microgrid performance and resilience.

This study presents a comprehensive analysis of a multi-architecture microgrid EMS for On-Grid, Off-Grid, and Weak-Grid topologies. The proposed EMS employs DRL to optimize energy dispatch and consumption, maximizing benefits of renewable resources through self-consumption. We compare state-of-the-art DRL algorithms (PPO, Rainbow DQN, Dueling DQN, Double DQN, and TD3) for multi-architecture microgrid EMS and introduce a curiosity-driven learning version for enhanced effectiveness.

We utilize Population-Based Training (PBT) for hyperparameter optimization (HPO) to improve DRL performance. PBT adapts hyperparameters during training, allowing efficient exploration of the hyperparameter space. Through EMS evaluation and result analysis, we identify the most effective DRL algorithm and optimal hyperparameters.

Our findings demonstrate DRL algorithms' potential in managing multi-architecture microgrids and PBT's effectiveness in optimization. This study offers valuable insights for developing efficient, robust EMSs and fostering sustainable, resilient energy systems, contributing to the advancement of microgrid optimization research.

3 - The utilization of seasonal storage in Burgenland

Markus Schindler, *Lukas Gnam*, *Markus Puchegger*, *Patricia Jasek*

The switch from fossil fuels to renewable energies is the crucial step on the way to a CO2 neutral society. However, one challenge in integrating renewable "energy sources" is their fluctuating production, as they are dependent on weather conditions. Furthermore, there is a strong seasonal component in the generation characteristics. In the consumption behavior there is also a seasonal component which is anticyclical to the generation. In Burgenland, the easternmost province of Austria, the energy system of the future is already emerging. In addition to the already existing wind energy plants, massive photovoltaic plants are currently being built. In order to be able to take the production surplus into the winter, the storage capacities must now be expanded. In this thesis the advantages of such storage systems for the energy system in Burgenland are investigated. Based on a mixed-integer optimization model, the use of storage systems (hydrogen, electric, heat) in hybrid parks in Burgenland is investigated.

■ TE-13

Thursday, 15:50-17:20 - ESA W(est) 121

Timetabling

Stream: Mobility and Traffic
Invited session
Chair: *Niels Lindner*

1 - A consistent modeling approach for travel chains in timetables

Stephan Buetikofer

The development of a transport service offer including different line types (e.g., fast trains, regional trains) is often decomposed into three successive steps. First, a system split is carried out so that each line type can be considered individually. Secondly, line planning is done and thirdly, a timetable is developed. These steps are carried out in several iteration loops involving coordinated activities across different companies, such as railway operators and infrastructure managers. Every step makes decisions about possible passenger travel chains (e.g., connections, travel time). We give a definition of a travel chain and discuss how it is created and concretized through the different steps. The literature often only discusses models for the individual steps, which is why there are few contributions to the coordination of travel chains across the different steps. Bad coordination can lead to the situation that the travel time in the computed timetable on a travel chain between start and destination is much longer than anticipated and customers, therefore, choose a different travel option. We want to discuss a new approach how to map the travel chains planned by transport operators in a consistent way across the different stages. For this purpose, we use flexible connections in a coordinated way (see Kroon et al. 2012). We will give a numerical example of a case study in the region of Lucerne to demonstrate our approach.

2 - Incremental Heuristics For Periodic Timetabling

Niels Lindner, Christian Liebchen

The timetable is the heart of any public transportation system, and therefore periodic timetable optimization is a highly relevant and ubiquitous planning task. Mathematically, this is expressed in terms of the Periodic Event Scheduling Problem (PESP), an NP-hard optimization problem, which is also challenging to solve in practice: Out of the 22 real-world-inspired instances of the benchmarking set PESPlib, none could be solved to proven optimality up to date. Lately, a new benchmarking library for integrated periodic timetabling and passenger routing, TimPassLib, has been published. The PESPlib railway timetabling instances arise as snapshots of some TimPassLib instances by fixing a passenger routing. Since the TimPassLib instances are annotated with data about lines and stations, this enables a deeper structural analysis of the PESPlib railway instances.

Based on this structural insight, we suggest two incremental heuristics for periodic timetabling in public transport: Firstly, we add lines one by one in descending order with respect to their passenger load. Secondly, we build the instance successively by starting with the busiest stations. In both versions, we construct a chain of subinstances of increasing size with the property that a feasible solution of a smaller instance can be expanded to a feasible solution of a larger instance. Since the smaller instances can be solved to optimality with mixed-integer programming techniques within a reasonable amount of time, we can thus quickly obtain excellent solutions, and we use partial fixing strategies to propagate these solutions to larger instances. First results indicate that this is a viable approach to obtain good quality periodic timetables.

3 - Improving dual bounds for periodic timetabling using graph contraction

Berenike Masing, Niels Lindner

In the context of computing periodic timetables in public transport, a mixed integer programming formulation of the Periodic Event Scheduling Problem (PESP) is the usual model of choice. Based on an event-activity network, i.e., a digraph whose nodes represent departure and arrival events of vehicles, while arcs represent activity types, such as driving, dwelling, turning, etc., the goal is to find the best timetable with respect to the weighted travel time. The problem is notoriously hard to solve in practice – none of the instances of the benchmark library PESPlib have been solved to optimality so far. As the instance size is one of the key issues, we propose a modification of a standard preprocessing technique: In theory, the two arcs incident with a degree-2 node can be contracted to a single arc without affecting the feasibility of the PESP instance. However, in order to keep the model equivalent, the objective function is then in general no longer linear in the travel time of the new arc, but only piecewise linear. We propose a new linearization of said non-linear objective function, which guarantees the travel time to be lower on the contracted arc than the separate arcs of the original instance. An optimal solution w.r.t. the contracted graph thus effectively underestimates the objective of the original. This preprocessing allows us to reduce the input size to such a degree that despite the underestimation, we can obtain significantly better dual bounds for the PESPlib instances.

4 - Scaling and Rounding Periodic Event Scheduling Instances To Different Period Times

Enrico Bortoletto, Niels Lindner

The Periodic Event Scheduling Problem (PESP) is a notoriously hard combinatorial optimization problem, essential for the design of periodic timetables in public transportation. PESP can be formulated as a mixed integer linear program, introducing technical integer variables to model the periodicity constraints. The coefficient of those variables is the period time, e.g., 60 for a period time of one hour with a resolution of one minute. In many application scenarios, lines with different frequencies have to be scheduled, leading to period times with many divisors. It then seems natural to consider derived instances, where the period time is a divisor of the original one, thereby smaller, and bounds are scaled and rounded accordingly. We first identify two rounding schemes: wide and tight. Wide rounding produces less restrictive instances, so that dual bounds of the rounded instance can be scaled to dual bounds of the original instances. Conversely, tightly rounded instances are instead more restrictive, but their feasible solutions offer primal bounds to the original instance. We then discuss the approximation performance of this method, in both theory and practice. Finally, although the combinatorial structures remain largely unchanged, we give evidence that the scaled and rounded instances are computationally easier to solve.

■ TE-14

Thursday, 15:50-17:20 - ESA W(est) 120

Electric vehicles: routing and locating charging infrastructure

Stream: Mobility and Traffic
Invited session
Chair: *Verena Stallhofer*

1 - An event-based model for the electric autonomous dial-a-ride problem

Verena Stallhofer, Sophie Parragh

Motivated by rising transportation related problems such as urban traffic congestion and pollution, we discuss the electric autonomous dial-a-ride problem (e-ADARP). The e-ADARP determines minimum-cost vehicle routes and assigns user requests with specified pick-up and drop-off locations to the vehicles. It is assumed that an electric and autonomous vehicle fleet is used for the ride-sharing services. The additional battery capacity and omitted maximum route duration constraints make the e-ADARP even more challenging to solve than the standard dial-a-ride problem (DARP). The weighted sum objective minimizing routing costs and total excess user ride times further complicates the problem. We develop a mixed integer linear programming model for the e-ADARP based on an event-based graph. The event nodes consist of tuples representing feasible user allocations to a vehicle as well as the current location of the vehicle. Arcs are only introduced between a pair of event nodes if the corresponding sequence of events is feasible. Our model is based on a recently proposed event-based formulation for the standard DARP from the literature. By using an event-based graph representation instead of a geographical one, capacity, pairing, and precedence constraints are implicitly applied. To strengthen the model, infeasible path constraints based on the maximum user ride time are adapted and added to the event-based model. We show that the benchmark instances are solved optimally within similar computation times as current, more sophisticated exact solution methods. Even for larger instances with up to 8 vehicles and 96 user requests, feasible solutions are obtained. With the additional valid inequalities, the model is able to yield improved feasible solutions for several instances.

2 - Driver Convenience Aspects in the Refueling Station Location Problem with Routing

Paul Göpfert, Stefan Bock

Drivers of electric vehicles (EVs) rely on a charging infrastructure that is still under development. However, in order to leverage the everyday use of EVs, even early stages of charging station networks have to provide convenient possibilities to get from origins to destinations. These routes shall require not more charging stops than necessary as well as avoid consecutive charging stops that are close by. In this talk, we integrate the two aspects in the well known Refueling Station Location Problem with Routing (RSLP-R). This optimization problem focuses on the selection of a limited set of charging stations from a given set of candidate sites with the aim to maximize the total covered weighted demand, given by origin-destination pairs. We evaluate the performance of a Branch-and-Cut algorithm on the arising new variants of the RSLP-R and obtain surprising results. While both considered aspects limit the number of feasible routes in comparison to the original problem, we see not only decreases, but also increases in terms of computation times that are needed to solve the problem instances to optimality. Furthermore, we provide insights on the impact on the obtainable objective values due to the even more constrained definition of feasible demand coverage in both new variants of the RSLP-R.

3 - Benders decomposition for planning dynamic inductive charging infrastructures on airport aprons

Inka Nozinski

Airport apron operations contribute to CO2 and noise emissions from the aviation system. Battery-powered electric apron vehicles, such as electrically operated apron buses, can be used to reduce these emissions. However, charging the vehicles results in long downtimes that can negatively impact airport operations. A potential solution to this problem is the dynamic inductive charging technology, which wirelessly charges vehicles while they are in motion. In order to implement a dynamic inductive charging infrastructure on the airport apron, it is important to determine where the necessary components of the technology should be placed. To answer this question, a strategic model was developed that aims to minimize the total investment. However, solving this model for real-world-sized instances with standard solvers results in extremely high computation times. For this reason, the use of Benders Decomposition for this problem is analyzed.

4 - Iterative local search for the location of static and dynamic EV charging infrastructure

Salma Hammani, Maximilian Schiffer, Paul Bischoff, Patrick Klein

Driven by climate change, rising environmental awareness, and financial incentives, municipalities increasingly aim to operate public transportation networks with electric vehicles (EVs). Against this background, we study the static and dynamic charging station location problem with semi-flexible vehicle routes. Here, dynamic chargers that enable charging while driving help to avoid idle times and improve fleet utilization. We assume fixed public transit stop sequences and timetables and determine cost-optimal charger locations with respect to charging costs and construction costs. To solve problem instances of realistic size, we propose an iterative local search (ILS) with a structured perturbation procedure to keep the number of visited charging configurations tractable. To evaluate each configuration, we show how to solve the remaining subproblem as a shortest-path problem with resource constraints to optimality by leveraging the A-star algorithm. We test our algorithm on (adapted) well-known benchmark instances and outperform a commercial solver up to a factor of 200 in computational time. Furthermore, we apply our algorithm to a case study for Munich. Our results indicate that dynamic charging can be a valuable addition to static charging.

■ TE-15

Thursday, 15:50-17:20 - R 0077, VMP5

Scheduling in Health Care 2

Stream: Health Care Management
Invited session
Chair: *Michael Römer*

1 - Predict, Tune and Optimize for Data-Driven Shift Scheduling with Uncertain Demands

Michael Römer, Felix Hagemann, Till Porrmann

When it comes to data-driven optimization under uncertainty, it is well-known that a classical predict-then-optimize pipeline in which point forecasts maximizing predictive accuracy are plugged into a deterministic optimization model typically leads to poor expected performance. In stochastic programming, one aims at obtaining better expected performance by explicitly representing the joint probability distribution in the optimization model, e.g. in form of a sample approximation. A downside of that approach is that it gives rise to large-scale models that are hard to solve, in particular in a combinatorial optimization setting. An alternative approach that recently attracted interest is to rely on "decision-focused" point predictions to be fed into a deterministic optimization model. This approach, referred to as decision-focused learning or predict-and-optimize, aims to train prediction models in a way that the expected performance of the decisions obtained with the (prediction-informed) deterministic model is maximized. In this paper, we propose to generalize this idea by optimizing not only parameters affecting the prediction but also additional parameters influencing other (non-stochastic) parts of the optimization model, again with the goal of maximizing expected decision quality, and refer to this approach as predict, tune and optimize. We demonstrate the usefulness of the approach for a multi-activity shift scheduling problem with demand uncertainty. We show that while decision-oriented tuning of point forecasts usually yields better results than a simple predict-then-optimize approach, adding the possibility to modify additional parameters considerably improves the expected performance which becomes competitive with a stochastic programming approach.

2 - Stochastic Optimization for Weekly Elective Surgery Planning

Raimund Kovacevic, Walter Hyll

We introduces and analyze a stochastic optimization model for planning elective surgeries of different (random), when emergency surgeries may intermit the planned schedule. Starting from a list of pending elective surgeries, the model selects elective surgeries for each day, making best use of avaliable operating rooms capacity. Based on the random durations of elective and emergency surgeries, the model aims at the contradicting goals of costs (goal of the hospital) and the lead time for finishing the list of elective surgeries (goal of the patients) and accounts for financial risk in this process.

3 - Surgery Scheduling in Flexible Operating Rooms by using a Convex Surrogate Model of Second-Stage Costs

Mohammed Majthoub Almoghrabi, Guillaume Sagnol

We study the elective surgery planning problem in a hospital with operation rooms shared by elective and emergency patients. This problem can be split in two distinct phases. First, a subset of patients to be operated in the next planning period has to be selected, and the selected patients have to be assigned to a block and a tentative starting time. Then, in the online phase of the problem, a policy decides how to insert the emergency patients in the schedule and may cancel planned surgeries. The overall goal is to minimize the expectation of a cost function representing the assignment of patient to blocks, case cancellations, overtime, waiting time and idle time. We model the offline problem by a two-stage stochastic program, and show that the second-stage costs can be replaced by a convex piecewise linear surrogate model that can be computed in a preprocessing step. This results in a mixed integer program which can be solved in a short amount of time, even for very large instances of the problem. We also describe a greedy policy for the online phase of the problem, and analyze the performance of our approach by comparing it to either heuristic methods or approaches relying on sampling average approximation (SAA) on a large set of benchmarking instances. Our simulations indicate that our approach can reduce the expected costs by as much as 20% compared to heuristic methods and is able to solve problems with 1000 patients in about one minute, while SAA-approaches fail to obtain near-optimal solutions within 30 minutes, already for 100 patients.

4 - Towards IoMT-driven Optimization for Home Health Care Planning

Seyedamirhossein Salehiamiri, Richard Allmendinger, Arijit De

The number of home caretakers is rising rapidly due to an increasing number of elderly people, recent pandemics, and the advancement of home health care facilities. Wearable medical devices and the Internet of Medical Things (IoMT) help health care managers monitor patients

in real-time and provide remote medical care. This reduces home visits and assist Home Health Care (HHC) companies to plan their resources. The paper addresses the HHC planning problem to allocate the optimal number of experts to patients while minimising the delay in visiting the patient, matching medical expertise with patient needs, and identifying the patient's visit sequence. To tackle this, a novel mixed-integer programming based mathematical model is proposed to reduce the total visit time for patients. This paper makes three key contributions while addressing the HHC planning problem, including (i) providing a formal definition of the problem and putting it in context with related work, (ii) initial analysis of several state-of-the-art heuristics to solve the problem, and (iii) discussing future research needed to facilitate the adoption of this technology by healthcare providers. By introducing Threshold Intervene Level (TIL), an extensive sensitivity analysis is performed to incorporate the real-time changes and propose alternate plans highlighting the possible deviations from the original Home Health Care plan. The results indicated that the application of computational intelligence combined with IoMT can decrease patient visitation time by 3.71% within a daily plan and hence leading to enhancing the efficiency of the Home Health Care planning.

■ TE-16

Thursday, 15:50-17:20 - R 0079, VMP5

OR Software in Practice

Stream: Software for OR
Invited session
Chair: *Ivo Hedtke*

1 - Designing a Tech Stack for OR Software
Ivo Hedtke

Developing OR software that is used productively comes with degrees of freedom as well as restrictions. We will examine the tackled decisions, pros and cons of options, constraints imposed by company rules, and lessons learned by DB Schenker's OR team over the past years as it developed and revised its tech stack: Programming languages: Trade-off between rapid development, runtime performance, and the programmer's expertise. Company standards restrict choices. A single language doesn't fit all purposes. Training is required. Frameworks: Building upon existing frameworks increases development speed and reduces bugs. Open-source licenses come with obligations. Directly using solver APIs enables all features and best performance, but results in a vendor lock-in. Input/Output: Data is stored or transmitted in a format. Frameworks make custom IO code obsolete and facilitate data exchange with other apps and technologies. Dependency management: Package managers are used to consume frameworks and provide own libraries. They are unavoidable if security and legal compliance play a role. They introduce risks in the software supply chain. Interoperability: Data Science and IT teams consume OR libraries, which requires integration into their tech stack. Benchmarking: Automatic tests of new releases on instances from literature and practice. Documentation: Has to be in sync with the code. Non-OR-specialists consume OR APIs. Own heuristics and implemented models can be intricate. Continuous Integration/Continuous Delivery: Static analysis helps identifying bugs. Style guides ensure productive collaboration. Unit, integration, and regression tests contribute towards zero-defect apps. Automatic dependency checks, app and documentation deployment, and benchmarking are performed.

2 - GAMS Engine SaaS: A Cloud-Based Solution for Large-Scale Optimization Problems
Stefan Mann, Frederik Proske

GAMS Engine SaaS is a cloud-based service that allows users to run GAMS jobs on a scalable and flexible infrastructure, currently provided by Amazon Web Services (AWS). It was launched in early 2022 and has since attracted a variety of customers who benefit from its features, such as horizontal auto-scaling, instance sizing, zero maintenance, and simplified license handling. GAMS Engine SaaS is especially suitable for workloads that require large amounts of compute power and can be adapted to many different scenarios. In this presentation, we show a case study of a large international consultant agency that uses GAMS Engine SaaS to run Monte-Carlo simulations of a large energy system model in response to varying climate change scenarios. We describe how they leverage the GAMS Engine API to submit and monitor their jobs, how they select the appropriate instance type for each job, and how they can use custom non-GAMS code on Engine SaaS. We also discuss the challenges and benefits of using GAMS Engine SaaS for this type of application, and provide some insights into the future development of the service.

3 - AIDe for Logistics: How does AI mitigate the risks?
Jan-Eric Zahnwetzer, Juliana Obynochnaya

Dramatically rising energy prices and disrupted supply chains are exacerbated by acute staffing shortages in the logistics field. This causes challenges - from fluctuating jobs'/parcels' volumes up to violations of operating cycles and the impossibility of planning. Graphmasters has pioneered the scientific discovery of AI algorithms to save the CEP. The key technology - collaborative routing - uses AI to put individual vehicles and commercial fleets into a mutual connection (principle of swarm intelligence) and enables them to shorten travel times, sharpen ETAs and save fuel for each trip. Delving into the problems of logistics companies, Graphmasters has developed many extra-features in the AI-driven optimization niche and the NUNAV AID solution unites them into one instrument for an efficient resistance to the existing volatility and for the ultimate business success. AID is an AI-driven automated dispatching system and allows to insert the whole spectrum of constrains and work parameters of a depot or a depots' fleet and to proceed with the planning and calculation of the optimal multistop routing sequences up to the current logics, defined by the CEP operators. The solution uniquely combines the adaptability to the CEP needs in a day-to-day precision and has endless potential for the most precise optimization and prediction calculations under given conditions. . . . Which economic and operational impact does this AI-driven approach make? How would it change the CEP performance and the balance sheets? This and more - to be answered within our presentation.

4 - A meta-planning engine for automatic parameter configuration in the Unified Planning Framework
Dimitri Weiß

The Unified Planning Framework (UPF) provides an abstraction layer for automated planning technology, enabling users to define planning problems in a planner agnostic manner and leverage any of the planning engines installed on their system. Planners have a multitude of parameters that can be adjusted that have an impact on performance, and selecting effective parameters for a given planning domain is a significant challenge. Manual parameter adjustments to a planning engine demand extensive domain knowledge and entail a significant time investment. Algorithm Configuration (AC) techniques have thus become commonplace for optimizing the performance of parameterized algorithms, with objectives that may range from reducing the time taken to identify a solution to enhancing the quality of the solutions generated. AC methods have demonstrated effectiveness across diverse problem settings, including automated planning, in finding high-quality parameter configurations. We propose to connect UPF with state-of-the-art AC tools through an "AC meta-planning engine." This engine acts as a standardized interface connecting users of UPF with AC methods to find high-quality configurations of UPF's planning engines and fine-tune the parameters to the specific domain they are solving. We show and compare the performance improvement through several AC methods using planning problem instances available in the UPF.

■ TE-17

Thursday, 15:50-17:20 - ESA O(st) 121

Discrete Optimization Applications II

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Lisa-Marie Manke*

■ TE-18

Thursday, 15:50-17:20 - ESA O(st) 122

Combinatorial Optimization and Machine Learning

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Nicole Megow*

1 - Connected k-Center and k-Diameter Clustering
Heiko Röglin

Motivated by an application from geodesy, we study the connected k-center problem and the connected k-diameter problem. These problems arise from the classical k-center and k-diameter problems by adding a side constraint. For the side constraint, we are given an undirected connectivity graph G on the input points, and a clustering is now only feasible if every cluster induces a connected subgraph in G.

Our main result is an O(1)-approximation algorithm for the connected k-center and k-diameter problem for Euclidean spaces of low dimension (constant d) and for metrics with constant doubling dimension. For general metrics, we get an O(log2 k)-approximation. We complement these upper bounds by several upper and lower bounds for variations and special cases of the model.

2 - Evaluating Stochastic Score Functions
Kevin Schewior, Benedikt Plank

We revisit the Stochastic Score Classification (SSC) problem introduced by Gkenosis et al. (ESA 2018): There are n tests. Each test can be conducted at some given cost, and it succeeds independently with some given probability. Further, a partition of the (integer) interval from 0 to n into a number of smaller intervals is known. The goal is to conduct tests so as to determine that interval from the partition in which the number of successful tests lies while minimizing the expected cost. Ghuge et al. (IPCO 2022) independently showed that a polynomial-time constant-factor approximation algorithm exists. We present a simple polynomial-time 5.829-approximation algorithm and discuss a few other directions such as adaptivity gaps.

3 - Speed-Oblivious Online Scheduling: Knowing (Precise) Speeds is not Necessary
Alexander Lindermayr

We consider online scheduling on unrelated (heterogeneous) machines, where each job has a job-dependent processing speed on each machine. Despite the relevance of these speeds for high-performance scheduling, there is a big discrepancy between how theory and practice handle them: while scheduling theory most commonly assumes that speeds are known to an algorithm, this is typically not the case in practice. Hence, algorithms that perform well in theory are often not applicable in practice. In this work, we propose new models and algorithms to bridge this gap. In particular, we introduce speed-oblivious algorithms, which do not rely on knowing (precise) processing speeds. We show strong impossibility results for clairvoyant and non-clairvoyant algorithms and overcome them in models inspired by practical settings: (i) we provide competitive learning-augmented algorithms, assuming that (possibly erroneous) predictions on the speeds are given, and (ii) we provide competitive algorithms for the speed-ordered model, where a single global order of machines according to their unknown job-dependent speeds is known. We prove strong theoretical guarantees and evaluate our findings on a representative heterogeneous multi-core processor. These seem to be the first empirical results for scheduling algorithms with predictions that are evaluated in a non-synthetic hardware environment.

This talk is based on joint work with Nicole Megow and Martin Rapp.

■ TE-19
Thursday, 15:50-17:20 - ESA O(st) 123

Branch-and-Cut-and-Price

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Esther Bischoff*

1 - Multi-robot task allocation with complex dependencies - a branch-and-price approach
Esther Bischoff, Robin Wöran, Simon Rothfuss, Soeren Hohmann

Time-extended multi-robot task allocation (MRTA) problems are combinatorial optimization problems that can be modeled as mixed integer linear programs and are closely related to vehicle routing problems. A common way to exactly solve time-extended MRTA problems are branch-and-price (BnP) approaches. Multiple BnP approaches exist that allow for the consideration of manifold constraints such as heterogeneous robotic teams or temporal restrictions. However, so far no complex tasks can be taken into account. Complex tasks have different possible decompositions into subtasks, of which at least one decomposition can be allocated to multiple robots. With the presence of complex tasks, in addition to task allocation and task scheduling, the problem dimension of task decomposition arises in time-extended MRTA problems.

We propose three novel methods how to handle complex dependencies within BnP approaches for time-extended MRTA problems. The "decomposition method" applies a decompose-then-allocate concept and handles task decomposition separately from task allocation and scheduling. In contrast to this, both the "decision variable method" as well as the "cluster method" incorporate the complex dependencies explicitly into the optimization model. For the decision variable method this is accomplished by modeling complex tasks as task trees by introducing AND- and OR-operators into the optimization model. In the cluster method additional weight parameters are introduced to model valid decompositions of complex tasks. Finally, an evaluation considering MRTA problems with different kinds and numbers of complex tasks demonstrates the applicability and effectiveness of the proposed methods.

2 - A Nested Decomposition Approach for the Multi-Stop Station Location Problem
Erik Mühmer, Miriam Ganz, Marco Lübbecke, Felix J. L. Willamowski

The Multi-Stop Station Location Problem (MSLP) deals with the placement of stations in a provided network such that sequences of stops can be traversed with respect to range restrictions. Whenever a station is visited the remaining range is reset. The goal is to minimize the installation costs of the stations and the total travel costs. The MSLP is related to problems that arise in telecommunications or transportation, e.g., charging station placement problems. Previously, we proposed a compact formulation solved by a standard MIP solver and a reformulation solved by Branch-Price-and-Cut. While the BP&C approach outperforms the compact formulation, it struggles to solve large real-world instances. Hence, in this work, we investigate a nested Branch-Price-and-Cut approach to solve the MSLP. The idea is to combine the advantages of outer and inner reformulations. To compare all three approaches regarding their strengths and drawbacks, we conduct experiments using multiple instance types.

3 - Branch-Price-and-Cut for the Set-Union Bin Packing Problem
Julia Wahlen, Timo Gschwind

Given a set of items, each requiring a set of elements, the set-union bin packing problem (SUBP) consists of grouping all items into a minimum number of bins such that each item is assigned to exactly one bin, while the number of distinct elements required in a bin does not exceed the bin capacity. The SUBP can be viewed as a generalization of the well-known bin-packing problem, in which items can share one or more elements in a non-additive fashion. In the literature, it has been addressed by various names such as pagination problem, job-grouping problem, parts-grouping problem, tool switching instants problem or bin packing with sharing. We propose a branch-price-and-cut algorithm for solving the SUBP. The column-generation pricing subproblem is modeled as a shortest path problem with resource constraints on a linear digraph and is solved with a dynamic-programming labeling algorithm where bounding is used as an acceleration technique. Valid inequalities are used to strengthen the formulation and dedicated separation heuristics are derived. Ryan and Foster branching is applied to finally ensure integer solutions. Preliminary computational results on benchmark instances from the literature are promising.

■ TE-20
Thursday, 15:50-17:20 - ESA W(est) 119

Auctions & Procurement II

Stream: Game Theory and Behavioral Management Science
Invited session
Chair: *Philippe Gillen*

1 - Exploiting uncertainty about the number of competitors in procurement auctions

Nicolas Fugger

Most of the literature on auctions assumes that bidders observe the number of competitors. However, this is typically not the case in procurement practice. Here, suppliers do not know the number of competitors. In contrast, the buyer can decide to observe the number of participating suppliers before selecting the auction format to get an informational advantage over suppliers.

In this paper, we investigate theoretically and experimentally if the buyer can exploit her private information about the number of suppliers or if she benefits from committing to a first-price auction independent of the number of suppliers. While standard economic theory with risk-neutral suppliers implies that the commitment does not affect the buyer's profit, the buyer benefits from commitment if suppliers are risk averse. In contrast, the buyer can exploit her private information about the number of suppliers if suppliers fail to understand the correlation between the actual number of suppliers and the buyer's format choice. Such an inability is, e.g., implied by cursed equilibrium reasoning.

Our laboratory experiments provide evidence that the buyer commands significantly better prices if she commits to a first-price auction. Furthermore, we observe behavioral patterns in line with risk aversion and cursed equilibrium reasoning. On the one hand, suppliers bid more aggressively than the risk-neutral Nash equilibrium predicts. On the other hand, they fail to interpret the buyer's auction format choice correctly.

2 - First-price sealed-bid vs. Dutch auctions for real-effort tasks

Dylan Gellert, Nicolas Fugger

When buying a special product, such as a complex technical component, buyers often rely on first-price auctions. In this project, we compare two auction formats: the first-price sealed-bid auction and the Dutch auction. Both auctions are among the most popular procurement mechanisms in practice. According to standard theory, the auction formats are strategically equivalent. However, there is mixed evidence from laboratory and field experiments indicating that the equivalence does not hold in practice. Recent theoretical developments consider loss aversion as a reason to explain this observation (Balzer et al, 2022). They predict that, in a procurement setting, the Dutch auction leads to lower prices than the first-price sealed-bid auction. We test the theoretical predictions in an experiment where the auctioned object is a real-effort task. We are the first to compare the Dutch and the first-price sealed-bid auction in a laboratory setup that does not consider induced values. With real-effort tasks, we ensure that the auctioned object (a loss of time) and the bids (a gain of money) are of two different dimensions of the consumption space. Multi-dimensionality is necessary when considering loss-aversion to be able to transfer the experimental results to the field (Lange and Ratan, 2010).

3 - Full Surplus Extraction from Colluding Bidders

Daniil Larionov

I consider a repeated auction setting with colluding buyers and a seller who adjusts reserve prices over time without long-term commitment. To model the seller's concern for collusion, I introduce a new equilibrium concept: collusive public perfect equilibrium. For every strategy of the seller I define the corresponding "buyer-game" in which the seller is replaced by Nature who chooses reserve prices for the buyers in accordance with the seller's strategy. A public perfect equilibrium is collusive if the buyers cannot achieve a higher symmetric public perfect equilibrium payoff in the corresponding buyer-game. In a setting with symmetric buyers with private binary iid valuations and publicly revealed bids, I find a collusive public perfect equilibrium that allows the seller to extract the entire surplus from the buyers in the limit as the buyers' discount factor goes to 1. I therefore show that a non-committed seller can effectively fight collusion even when she faces patient buyers, can only set reserve prices and has to satisfy stringent public disclosure requirements.

■ TE-21

Thursday, 15:50-17:20 - ESA W(est) 122

Forecasting Models, Theory, Case Studies

Stream: Analytics, Forecasting and A.I.
Invited session

Chair: *Hans Georg Zimmermann*
Chair: *Davina Hartmann*

1 - The value of accurate and coherent forecasts for logistics

Benedikt Sonnleitner, Nikolaos Kourentzes

Optimization under uncertainty often assumes a distribution or draws thereof to describe the uncertain parameters. Forecasting can provide these based on data, and accordingly often a predict then optimize scheme is used where the output of forecasts serve as input to the downstream optimization model which delivers a decision. Thereby the uncertainty estimate of the forecast is itself a prediction and cannot be assumed to be perfectly accurate. In this framework we investigate the impact of inaccurate point forecasts, uncertainty estimates, and incoherency when forecasts on different levels are not aligned, on the example of a logistics network. Further we give some accuracy benchmarks on Machine Learning based and statistical forecasting methods. We show that forecasting inaccuracy has a substantial impact on the actual cost of decisions and the actual costs differ substantially from the theoretically optimal cost. Our results suggest that forecasters should tailor their forecasting algorithms and evaluations to the downstream optimization and optimizers should evaluate decisions given inaccurate forecasts instead of assuming correctly calibrated distributions.

2 - Causal versus Causal-Retro-Causal Forecasting

Hans Georg Zimmermann, Ralph Grothmann

Causality is a paradigm which models the future as a consequence of the past while retro-causality turns around causality in time. From the viewpoint of data this sounds unreasonable because we have only data of the past. But including a-priori structures the reasoning might change: In this talk we will share a mathematical structure of this concept, some experiments and insights.

3 - Using Food Demand Forecasts to Reduce Food Waste: A Case Study of Company Canteens

Nicki Lena Kämpf

Food waste is a major global challenge that has negative environmental, social, and economic impacts. In Germany alone, the Federal Statistical Office reports that eleven million tons of food waste were generated in 2020. In addition to the ethical concerns around wasting food while millions go hungry, food waste contributes significantly to greenhouse gas emissions and the depletion of natural resources. Several studies have demonstrated the potential of predictive analytics in the food industry in general. However, scientific research in the field of system and company catering remains limited. This study aims to bridge this gap by demonstrating the applicability and performance of predictive analytics for company canteens using a real-world dataset. The study shows that accurate predictions are possible with minimal data preprocessing and time spent on feature engineering, implying that satisfactory forecasting performances could be achieved in the whole branch with limited resources. This presents economic benefits, particularly for companies with multiple canteen locations. Predictive analytics can be automated for multiple canteens and thus not only reducing food waste and associated production costs, but also give insights into the drivers of demand and freeing up employee time for other tasks instead of forecasting and planning.

■ TE-23

Thursday, 15:50-17:20 - ESA W(est) 222

Matheuristics and PSO

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session

Chair: *Nils-Hassan Quttineh*

1 - A matheuristic for a bi-objective covering problem

Nils-Hassan Quttineh, Torbjörn Larsson

We consider a large-scale bi-objective covering problem that arises in a surveillance application and has the two conflicting goals of cost and degree of coverage. The problem generalises the standard set covering problem, is computationally very demanding, and does in practice not allow the use of optimizing methods. An approximate Pareto frontier can however easily be found by a standard constructive greedy heuristic, which gradually increases coverage at the expense of increased cost. This approximate frontier becomes of high quality in the early

greedy steps, when the coverage is low, but typically diverges away from the Pareto frontier when full coverage is approached; this is due to early greedy decisions that later turns out to have been poor. To mitigate this outcome, we here investigate a new constructive matheuristic, which allows revoking decisions from earlier steps. We compare its performance with the previous solution technique. Since the standard set covering problem is a special case of the studied problem, the new constructive matheuristic can also be used to find approximate solutions to the former.

2 - An Efficient Matheuristic for the Robust Berth and Quay Crane Assignment Problem at Seaside Container Terminals Respecting Uncertain Numbers of Quay Cranes

Abtin Nourmohammadzadeh, Stefan Voss

In this work, we focus on the integrated problem of berth and quay crane assignment at seaside container terminals. As the number of available quay cranes at berths can change due to unexpected issues such as breakdowns, an uncertainty in this respect is considered in our model and robust optimisation is applied. This uncertainty appears on the right hand side of a constraint in the presented mathematical model and leads to a robust optimisation problem which has not been sufficiently investigated before. Five different scenarios are regarded for the number of available quay cranes during each period.

A set of synthetic problem instances of various sizes are randomly generated. A matheuristic algorithm consisting of mathematical programming of partial models and a particle swarm optimisation (PSO) approach is developed to tackle the problem. The model and algorithms are programmed in Python, and Gurobi is used as a powerful standard solver. The results of the proposed matheuristic is compared with the outcomes of the pure mathematical programming, pure PSO and a state-of-the-art solution methodology from the literature. The analysis of results confirms the good performance of our proposed matheuristic.

3 - Adaptive particle swarm optimization based on fitness landscape analysis

Malek Sarhani

Particle swarm optimization (PSO) is a swarm intelligence approach that is considered one of the most effective metaheuristics for solving continuous optimization problems. Various adaptive approaches have been proposed to enhance PSO. In fact, the improvement and adaptation of PSO to deal with current optimization challenges, such as machine learning parameter tuning, is a popular topic. However, one of the main issues in this regard is specifying the criteria for setting the adaptive algorithm. That is, the adaptive algorithm should consider historical information for better handling of the exploitation-exploration dilemma.

Fitness landscape analysis (FLA) is an effective way to measure these criteria, as it focuses on understanding algorithm performance and the factors that contribute to it. Many features have been proposed to assess fitness landscape difficulty, with ruggedness generally referring to the number and distribution of local optima. The inclusion of FLA in PSO has several potentials, as illustrated in (Engelbrecht et al., 2021).

The aim of this paper is to propose an adaptive variant of PSO based on FLA using an estimation of the ruggedness factor. To achieve this goal, we aim to develop a multi-step approach. Firstly, we calculate the ruggedness factor. Secondly, we identify the appropriate PSO strategy by adopting the appropriate adaptive rule to update PSO parameters based on the literature. Lastly, we enhance the exploration and exploitation management capacity of the algorithm by implementing the appropriate updates.

Engelbrecht, A. P., P. Bosman, and K. M. Malan. "The influence of fitness landscape characteristics on particle swarm optimisers." Natural Computing (2021): 1-11.

■ TE-24

Thursday, 15:50-17:20 - ESA O(st) 120

Scheduling Problems

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Philipp Warode*

1 - Competitive Kill-and-Restart and Preemptive Strategies for Non-Clairvoyant Scheduling

Philipp Warode, Sven Jäger, Guillaume Sagnol, Daniel Schmidt genannt Waldschmidt

We study kill-and-restart and preemptive strategies for the fundamental scheduling problem of minimizing the sum of weighted completion times on a single machine in the non-clairvoyant setting. First, we show a lower bound of 3 for any deterministic non-clairvoyant kill-and-restart strategy. Then, we give for any b > 1 a tight analysis for the natural b-scaling kill-and-restart strategy as well as for a randomized variant of it. In particular, we show a competitive ratio of 6.197 for the deterministic and of 3.032 for the randomized strategy, by making use of the largest eigenvalue of a Toeplitz matrix. In addition, we show that the preemptive Weighted Shortest Elapsed Time First (WSETF) rule is 2-competitive when jobs are released online, matching the lower bound for the unit weight case with trivial release dates for any non-clairvoyant algorithm. Using this result as well as the competitiveness of round-robin for multiple machines, we prove performance guarantees smaller than 10 for adaptions of the b-scaling strategy to online release dates and unweighted jobs on identical parallel machines.

2 - Performance impact of constraint revisions on a MILP formulated hearing scheduling problem.

Ieke Schrader, Erwin W. Hans, Marco Schutten

The courts within the judicial system involve a labour-intensive service supply chain, where planners are faced with the challenge to maintain accessibility for litigants while balancing the workloads of court staff (clerks and judges). We focus on the tactical level of this planning problem. We introduce the hearing scheduling problem (HSP), which is to develop a block schedule to optimally allocate staff to court case types. Given such a block schedule, in the subsequent operational Case Booking Problem (CBP), cases can then be assigned to these blocks. To solve the HSP, we present an MILP formulation, for which the constraints were based on the judicial domain of family law. For other domains of law, the HSP has many similarities, but may have some additional or different constraints, which we expect can be accommodated by adjusting our model.

In our experiments we focus on the situation of the court of family law in the Netherlands. Several of the HSP planning constraints stem from 'rules of thumb', which have originated over time. We perform experiments in which we challenge these constraints by assessing variants or degrees of relaxation of those constraints. We discuss the performance impact of these constraint revisions, and present new rules of thumb for the HSP in the context of family law.

3 - Load Balancing: The Long Road from Theory to Practice

Klaus Jansen

There is a long history of approximation schemes for the problem of scheduling jobs on identical machines to minimize the makespan. Such a scheme grants a (1+[U+03F5])-approximation solution for every [U+03F5]>0, but the running time grows exponentially in 1/[U+03F5]. For a long time, these schemes seemed like a purely theoretical concept. Even solving instances for moderate values of [U+03F5] seemed completely illusional. In an effort to bridge theory and practice, we refine recent ILP techniques to develop the fastest known approximation scheme for this problem. An implementation of this algorithm reaches values of [U+03F5] lower than 2/11≈18.2% within a reasonable timespan. This is the approximation guarantee of MULTIFIT, which, to the best of our knowledge, has the best proven guarantee of any non-scheme algorithm. This is joint work with S. Berndt, M. Deppert, and L. Rohwedder.

4 - An Introduction to Busy Time Minimization in Temporal Bin Packing

John Martinovic, Nico Strasdat

Given a set of jobs (or items), each of which being characterized by its resource demand and its lifespan, and a sufficiently large number of identical servers (or bins), the busy time minimization problem (BTMP) requires to find a feasible schedule (i.e., a jobs-to-servers assignment) having minimum overall power-on time. Although BTMP can be classified as a variant of temporal bin packing, it actually represents an independent branch of research since, for instance, the related solution sets are generally different. Typically, such considerations (and generalizations of it) are very important in data center workload management to keep operational costs low. Hence, finding efficient solution techniques for BTMP is a relevant topic in discrete optimization, both from a theoretical and a practical point of view. In this work,

we give an overview of heuristic and exact approaches for the problem under consideration, establish a new combinatorial flow-based formulation, and discuss some improvements of the presented ILP models. Finally, the effects of our contributions are demonstrated based on computational tests involving classic benchmark sets.

■ TE-25

Thursday, 15:50-17:20 - ESA O(st) 222

Reinforcement Learning

Stream: Simulation, Reinforcement Learning and Quantum Computing
Invited session
Chair: *Maximilian Moll*

1 - Balancing Performance and Explainability in Subgoal-Based Reinforcement Learning for StarCraft 2
Viktor Görlitz, Philip Maurice Scheidig, Christian Schwede

In reinforcement learning, increasing agent explainability is crucial for real-world applications. Subgoals are a common approach to guide agents towards specific behaviors and improve sample efficiency by providing additional rewards. However, subgoal granularity or density affects performance and explainability. This paper analyzes the relationship between granularity and performance/explainability of subgoal-based agents. The goal is to find an optimal granularity level that balances the agent following the expected path while allowing it enough freedom to maximize its performance in complex and adversarial environments. Using StarCraft 2 as an example, we identified two factors influencing this relationship: task difficulty and environment variance. With these factors, a decision matrix was constructed to help determine the optimal number of subgoals. Overall, our work contributes to a better understanding of the role of subgoals in reinforcement learning and offers practical guidance for designing subgoal-based agents.

2 - From Shogi and Chess to Reinforcement Learning: A study of NNUEs in more general settings
Philipp Triebold, Maximilian Moll, Hans-Georg Enkler, Stefan Wolfgang Pickl

The continued development of evaluation functions for use in chess and shogi engines resulted in the development of Efficiently Updatable Neural Networks in 2018 by Yu Nasu. These utilise the full potential of modern processors foregoing the need for specialised hardware and thus decreasing cost and energy consumption. There are three central optimisations, leveraging the sparsity and redundancy in the encoding, lowering the bit width and pivoting all calculations to integers, and lastly using advanced vectorisation with single instruction multiple data registers. These optimisations are evaluated for their contribution to Efficiently Updatable Neural Networks and how they could impact efficiency and speed in different environments. Finally, the optimisations are implemented in Python and C++ to test their real-world benefits.

3 - Statistical Analysis of Reinforcement Learning Training
Maximilian Moll, Matthias Schilling, Stefan Wolfgang Pickl

One of the most urgent challenges in reinforcement learning research is the lack of reproducibility. This impacts scientific progress due to the difficulty of comparing different results. Furthermore, it also introduces additional complexity to developing and testing because it is not immediately clear whether a different result is caused by a significant change in procedure or a difference in the random seed. Lastly, the application of RL in practice is made more difficult because it is hard to assess the result of using RL for a task. Therefore, to further the understanding of the training behavior of Reinforcement Learning agents, we analyze the training of agents playing the established baseline environment Taxi. Each agent is trained using the same Tabular Q-Learning procedure with fixed hyperparameters and fixed initializations. The trained agents' evaluation performance, as well as the training progress itself, are then compared to identify critical differences in characteristic behavior. Subsequently, we extend this comparison to include different hyperparameter settings to investigate the impact on the identified training behavior.

Thursday, 17:30-19:00

■ TF-01

Thursday, 17:30-19:00 - ESA A

GOR Annual Meeting

Stream: PC Stream
Meeting session

Friday, 8:30-10:00

■ FA-02

Friday, 8:30-10:00 - ESA B

OR in Logistics and Supply Chain Management

Stream: Decision Analysis and Support
Invited session
Chair: *Julia Schleier*

1 - Designing reverse logistic networks for expanded polystyrene waste from building insulation
Julia Schleier, *Grit Walther*

Efficient recycling of secondary materials is crucial for the transition towards a circular economy. However, certain waste materials such as expanded polystyrene (EPS) contained in external thermal insulation composite systems (ETICS) pose challenges as the waste stream is spatially dispersed and high-quality recycling options are still lacking. In order to manage the increasing EPS-ETICS waste volumes in the future, advanced waste treatment technologies must be installed including chemical recycling pathways. Moreover, corresponding reverse logistics networks are needed in order to efficiently manage these spatially dispersed waste streams. To address these challenges, we propose a strategic planning approach for the design of reverse logistics networks for EPS-ETICS that considers promising recycling technologies and the spatial distribution of future EPS-ETICS waste. Our approach is based on a multi-period MILP that takes into account decisions on technology, capacity, and location, as well as decisions regarding material transformations within the network. We aim to determine a cost-effective reverse logistics network configuration that meets regulatory requirements. By applying the model to a German case study, we provide valuable insights for decision-makers regarding optimal strategies for managing EPS-ETICS waste. Furthermore, we analyze uncertain regulatory and market developments to consider possible trajectories. By integrating early-stage recycling options, our approach contributes to fostering more sustainable waste management and promoting the circular economy for EPS-ETICS.

2 - Simulation optimization to investigate the potential of mobile food hubs and crowd logistics to facilitate product adoption in short food supply chain
Florian Cramer, *Christian Fikar*

This work investigates whether platform services that combine mobile food hubs and crowd logistics, i.e., mobile transshipment nodes and occasional drivers, can provide growth opportunities (e.g., faster product adoption) for micro, small, and medium-sized enterprises (MSMEs) in short food supply chains. To this end, a decision support system based on simulation optimization is introduced. The simulation builds on agent-based simulation and system dynamics elements to help understand if and how these platform services can facilitate product adoption and enable entrepreneurs in the food sector. Using simulation optimization, it can be determined what MSMEs should consider participation and how mobile food hub operations should be scheduled.

3 - Combining data analytics and aggregation-disaggregation analysis for effective decision-making in the industry 5.0
Andrej Bregar

This research introduces a methodology for the inference and specification of multi-criteria decision-making (MCDM) models, which we can apply in business and production processes for Industry 5.0. Holistic decisions are inferred from big data on process activities, service use, IoT measurements, and past decision ontologies. Since patterns in big data might not directly help decision-makers make well-informed choices, regression methods for the indirect derivation of preferential parameters from sets of correlated parameters or historical alternatives are used to obtain objective MCDM models. The aggregation-disaggregation analysis consolidates the inferred models with the subjective judgments of human decision-makers. This approach allows for constructive learning and gives structure to problem-solving. The derived MCDM models enhance intuition by reflecting human decision-making and problem-solving patterns. They correspond to the paradigm of Industry 5.0, which complements the concepts of automation, big data, and AI with human-centricity. It is hence an additional aim of this work to introduce a generic decision-making process for Industry 5.0. We apply it in a case study on the dynamic electricity supply market. In this use case, we utilize machine learning to predict electricity consumption. We then implement the disaggregation analysis to automatically construct objective AHP and utility models with multiple criteria, such as monthly costs and energy supply reliability. These models are presented to the human in the loop to enrich them with personal preferences. The final research goals are to evaluate the approach with a simulation study and define a theoretical VUCA-based model for change and knowledge management in an uncertain and disruptive world.

4 - Modeling economic uncertainty in EoL electric vehicle battery pathways from an OEMs perspective
Sonja Rosenberg, *Sandra Huster*, *Frank Schultmann*

The upcoming European battery regulation will set legal pathways for circular End-of-Life (EoL) treatment of electric vehicle batteries (EVBs). Existing research and quantitative modeling have primarily dealt with planning battery recycling networks that involve destructive disassembling and recycling. Apart from obligatory recycling, market players may choose to remanufacture or repurpose EBVs if economic profitability is expected. Due to a not-yet-existing market, uncertainty about future demand, costs, and potential revenues from recycling or remanufacturing/repurposing arises. Thus, an investment in reverse network activities for EVBs involves high uncertainty. We address the problem by developing a two-stage stochastic programming model with disassembling technology selection in a reverse network context. Disassembling may either be destructive or non-destructive. Non-destructive disassembling allows to win functioning battery modules that can be reused for remanufacturing or repurposing. Nevertheless, the number of functioning battery modules depends on the size and quality of disassembled battery systems. The model's first stage decisions are investments in capacity blocks of disassembling technologies at selectable locations. The second-stage decisions are allocation and treatment decisions on battery systems. The goal function is designed as profit maximization. We apply the model to a case study setting from an OEM's perspective in Germany. A particular focus is given to modeling the dynamics of the expected EoL market, namely distinct battery types (size and cell chemistry), multiple planning periods, and capacity adjustment of the treatment options.

■ FA-03

Friday, 8:30-10:00 - WiWi A, VMP5

Sustainable and Efficient Logistics: Insights into Electric Vehicle Routing and Waste Collection

Stream: Logistics
Invited session
Chair: *Francessco Taverna*

1 - Modeling and solving a heterogeneous fleet multi-trip electric vehicle routing problem
Sophie Parragh, *Martin Hofwimmer*

The heterogeneous fleet multi-trip electric vehicle routing problem that we address is motivated by a problem situation arising in mid-range road freight transport. A set of customers has to be supplied from a central warehouse with a fleet of heterogeneous vehicles, some of which are electric vehicles. Loading and unloading times are proportional to the quantity loaded. Each vehicle may serve multiple trips during its operating time. Vehicles have a maximum capacity as well as a limited driving range. Re-charging/re-fueling is only possible at the depot between consecutive trips to customers. The objective is to minimize the total operating costs which are vehicle type dependent. We propose a compact model as well as a set covering based formulation. The latter is solved on a set of trips that are generated by heuristic constructive procedures and combined with a variable neighborhood search based algorithm. The developed approaches are used to evaluate fleet size and mix decisions on real-world data from Upper Austria.

2 - Waste collection with EVs: a MILP formulation
Francessco Taverna, *Luca Di Gaspero*

The rising carbon emissions made clear that achieving sustainable mobility can no longer be delayed. To this aim, we required emission-free heavy-duty urban trucks, as they impact significantly on carbon emissions despite their small overall quantity. In this work, we focus on garbage collection with an electric fleet, namely, on optimizing the collection routes of electric trucks. Our research focuses on exact solution approaches, which are used in a few studies due to the complexity of the problem. Thus, our study aims at filling the lack of research into exact algorithms for the E-VRP-NL.

Starting from [1], we propose a MILP formulation for the electric vehicle routing problem with heterogeneous charging stations and non-linear charging functions (EVRP-NL), which considers the effect of load on energy consumption. The model describes the recharging process without using binary decision variables, which represents a novelty in the literature to the best of our knowledge. In most cases, the tests on Montoya's small instances, up to 40 bins, resulted in better routes with higher charging time utilizations than those found by the meta-heuristics. The former results are obtained within 30 minutes of computational time.

We created new instances using the locations of litter bins to test our model on real industrial cases. We exploit the road layout to reduce the complexity of the former instances and bring some operational constraints described by waste collection companies into the model. These tests make a contribution to the literature as few studies deal with real-world instances.

[1] Bruglieri, M., Mancini, S., Pisacane, O.: More efficient formulations and valid inequalities for the green vehicle routing problem. T. Research 105, 283-296 (2019)

3 - Periodic vehicle routing problems with intermediate facilities: A solution method and real-world applications in waste collection

Christina Hess, *Alina-Gabriela Dragomir*, *Karl Doerner*

This work is concerned with the solution of real-world waste collection problems which can be modelled as periodic vehicle routing problems with intermediate facilities (PVRPIF). The waste is collected with a fleet of homogeneous vehicles located at a central depot and delivered to incinerators or other waste processing facilities. Trips to these intermediate facilities must be scheduled mid-route, when necessary, and at the end of the route, so that the vehicles return to the depot empty. Since most locations do not have to be visited every day, a planning horizon of several days is considered. In most periodic vehicle routing problems, a fixed number of visits and a small set of possible visit schedules per customer are given. We study the effect of allowing varying degrees of flexibility both in the usage of the intermediate facilities and in waste collection frequencies and schedules using a set of instances inspired from real-world cases. The goal is to minimize the total distance while considering vehicle capacities, avoiding overflows, and adhering to real-world constraints regarding the intermediate facilities such as minimum quotas and capacity limits. We implement an adaptive large neighbourhood search algorithm (ALNS) to solve the PVRPIF which uses problem-specific operators to adapt visit frequencies and schedules, and a heuristic procedure to insert the intermediate facilities. We present real cases with up to several thousand collection nodes and report improvements and insights from applying our method to them. Additionally, we show the effectiveness of our method using a set of smaller benchmark instances from the literature.

■ FA-04

Friday, 8:30-10:00 - WiWi B1, VMP5

Central vs. Distributed Systems

Stream: OR in Engineering
Invited session
Chair: *Julius Breuer*

1 - Integrating simulation and numerical analysis in the evaluation of priority queueing system using generalized stochastic Petri nets.

Sedda Hakmi, *Lyes Ikhlef*, *Ouiza Lekadir*, *Djamil Aïssani*

In this paper, we propose a stochastic modeling of Priority queuing models through the concept of including the Generalized Stochastic Petri Nets algorithm (GSPN). GSPN are used as an effective method for portraying synchronization, a concurrency between different system activities and support for complexity queue systems.

The expressive power of the GSPN formalism provided us a very detailed modeling and semantically accurate which reduces the complexity of these priority systems and allow us to examine how this representation can be used to find the main steady state performance indices and obtain several numerical results.

2 - Efficient and Quite: Optimisation of Ventilation Systems by coupling Airflow with Acoustics in a Multipole Approach

Julius Breuer, *Peter Pelz*

Ventilation systems are used to ensure a good indoor climate even in increasingly airtight buildings. It is predicted that ventilation systems will be installed in 90 % of all new buildings in Germany by 2035 in order to achieve the EU's climate targets. To design energy-efficient ventilation systems, topology decisions have to be made about the number, size, location and interconnection of fans and volume flow controllers, and operation under different load scenarios has to be anticipated. This leads to enormous degrees of freedom (combinatorial explosion). Therefore, instead of conventional planning, the systems can be modeled and optimised using discrete optimisation. The objective then is to minimise the systems' life-cycle costs. The resulting optimisation problem is a 2-stage stochastic Mixed-Integer Nonlinear Problem. Preliminary work has confirmed the enormous potential of the approach to reduce life-cycle costs by up to 23 %. However, so far consideration of acoustic characteristics has been lacking. The noise from a ventilation system must not exceed certain sound pressure levels in rooms. To integrate the acoustic wave phenomena into the optimisation, this paper models sound propagation from the duct network to the rooms as a network flow problem. To achieve the noise limits, silencers are included in the optimisation problem. Then, airflow and acoustic wave propagation are coupled in a multipole approach. The difficulty in modeling lies in the strong nonlinearities in the acoustic equations. To overcome these, the mathematical structure of the model is exploited. The results show a tremendous increase in calculation time. However, the coupling is an important step that takes mathematically supported designing of ventilation systems to a new level.

■ FA-06

Friday, 8:30-10:00 - ESA C

Inventory routing

Stream: Supply Chain Management
Invited session
Chair: *Stefan Minner*

1 - Inventory redistribution for promotional products with demand learning

Mahsa Abbaszadeh Nakhost, *Gudrun Kiesmuller*, *Stefan Minner*

The retail industry often offers promotional products for a short period of time to attract more customers. As these products have not been offered before, retailers lack historical demand data for proper forecasting. Moreover, due to seasonality, such products have highly uncertain and non-stationary demands and a long lead-time. Therefore, retailers usually have only a single ordering opportunity. To improve the trade-off between ordering too few and facing stockouts or ordering too many and selling overstock at a markdown, we propose a one-time lateral transshipment among retailers during the selling horizon. Specifically, we consider the distribution of a single product among N retailers from a central warehouse or distributor, without the option of keeping parts of the stock at the central warehouse. At a predetermined time during the selling horizon, after observing the demand, a one-time redistribution among the retailers is carried out. To better model demand uncertainty for such products, we consider non-stationary and stochastic demand with unknown mean. Additionally, we update the demand distribution, non-homogeneous Poisson Process, using Bayesian methodology before making the transshipment decision. We prove that for the profit maximization problem, the expected second-period profit is L♮-Concave in the value of transshipment, and solve the discrete transshipment problem to optimality for N retailer. Our numerical analysis shows that expected profit is

first increasing and then decreasing with time of transshipment. Moreover, decreasing demand rate leads to earlier and increasing demand rate leads to later transshipment. We evaluate our methodology by implementing it in a real-world case study, and we observe significant improvement in profit.

2 - An integrated model for a distributed network of production systems with inventories and central replenishment unit: Queues - Inventories - Transport - Location

Hans Daduna

We consider production systems which manufacture single products on a make-to-order basis where each production process needs an item of raw material from an associated local inventory. A central replenishment server generates the raw material which is delivered to the inventories according to a load-dependent adaptive schedule and transported by a fleet of trucks. The locations of the production systems are prescribed and transportation times from the central replenishment server to the locations of the production systems are incorporated in the model.

Results: (i) Under some natural (standard) assumptions on the random nature of the system's behaviour and for prescribed location of the center we compute the steady state distribution of the system. The explicit result seperates the interacting components asymptotically and in the stationary state. (ii) For given positions of the procuction systems we find a (nearly) optimal location for the central replenisment unit incorporating the effects of transportation delay, varying demand, depletion of inventories, and congestion due to random influences. Moreover, for given demand streams and production capacities we determine the size of the fleet needed to support the production-inventory systems.

3 - Cyclic Stochastic Multi-Product Two-Echelon Inventory Routing with Inventory Policies for Medical Supply

Alexander Rave, Pirmin Fontaine, Heinrich Kuhn

Hospitals store a variety of medication to ensure the treatment of patients, whose demand in medication, however, is uncertain. Due to this inventory holding, large costs arise, which can be reduced by optimizing inventory and delivery patterns, simultaneously. In general, the procurement and supply of hospitals and clinics follows a two-echelon structure: A larger central clinic orders medication and distributes them to multiple surrounding smaller clinics, with each clinic having its own independent inventory policy. Within the inventory policies, there may occur instant replenishment orders to prevent shortages.

We represent this problem setting as a multi-product cyclic two-echelon inventory routing problem with stochastic demands that combines the routing decision with two different inventory policies. We formulate a two-stage stochastic program with emergency deliveries as recourse decision that decides on the cost-optimal cyclic routing and reorder points. To solve larger instances, we develop a specialized adaptive large neighborhood search that integrates an algorithm to compute local optimal reorder points for each routing in each iteration.

We show results from a case study conducted at a large German hospital that plans to use drones instead of trucks for emergency delivery. The simultaneous optimization of inventory and routing of both echelons reduces average costs by 58.4% and 15.9% for the surrounding clinics and the central clinic, respectively, compared to the status quo. A sensitivity analysis shows that the use of drones for emergency delivery decreases the average inventory of surrounding clinics by 1.7% to even 100% for expensive and rarely used medication resulting in total cost savings of 29.8%.

4 - Closed-loop supply chain optimization for reusable packaging

Vivien Schoepf, Arne Strauss

The concept of the circular economy has gained importance in many industries, with closed-loop supply chains (CLSCs) as key enabler to the effective implementation and operation of such systems. This research project focuses on a variation of the Inventory Routing Problem (IRP) in secondary reusable packaging, illustrated on the example of the food industry. The scenario considers a triangular relationship between a manufacturer that leases reusable grocery crates, food producers and urban supermarkets, from which the crates must be collected after use. The supermarkets report their need for collection of empty crates when they have reached a certain capacity limit. The transport (forward and reverse) and processing (e.g., washing) of the collected crates is managed by the leasing company. As this is a pay-per-cycle business model, the leasing company is faced with a trade-off between the fast collection of empty crates (to fulfil the demand of the food producer) and efficient transport routes. This scenario is depicted under the use of Markov decision processes and simulations. Different demand management techniques are further applied at the supermarkets, such as a variation of collection periods. Thus, the focus of the work lies not only on CLSCs, but also intersects the areas of demand and inventory management. Particularly in cities, the density of demand allows for the deployment of CLSCs; however, the application of demand management techniques have only been scarcely explored in the field of CLSCs or reverse logistics. Inventory management considerations add to a holistic perspective and provide managerial implications for practitioners in the industry.

■ FA-07

Friday, 8:30-10:00 - ESA J

Banking and Finance

Stream: Financial Management and Investments
Invited session

Chair: *Tim Herberger*

1 - The Relationship of Board Diversity and Stock Performance in Monistic and Dualistic Board Structures: Results from Germany and UK

Tim Herberger, Andreas Oehler

The analysis of the relationship between board diversity and corporate performance is a well-documented area of research. Our analysis on the stock markets in Germany and UK delivers additional insights by taking into account different corporate constitutions (monistic and dualistic) as well as additional diversi-ty factors (e.g. dispersion of the average age in the respective board) and diversity potential factors (e.g. entry and exit of members of a board during a fiscal year). In addition, we take the stock price performance into account as a company performance proxy, because this can be observed more easily by non-professional investors than Tobin's Q, which is commonly used in former studies. Our results over a period from 2005 to 2018 show that there is no significant difference between monistic and dualistic corporate constitutions in terms of a possible relationship between diversity and corporate performance. Additional-ly, our results confirm former studies that the size of a top management group (executive board, superviso-ry board as well as management) is significantly negatively related to company performance in the long run. However, no significant correlation for the first time can be found between changes in a board in a fiscal year and company performance.

2 - When do retail investors apply leverage?

Matthias Pelster, Rico Heuchel

Leverage significantly increases the volatility of investors' returns. Over the past years, trading with leverage has increased significantly. Yet, it is unclear to which positions investors' apply leverage. We provide experimental and archival evidence suggesting that investors apply less leverage to more volatile assets and more leverage to positively skewed return distributions. Overall, our findings suggest that investors pursue a specific target for the volatility of their returns.

3 - Textual Disclosure in Prospectuses and Investors' Security Pricing

Philipp Klein, Jörn Debener, Arved Fenner, Steven Ongena

We investigate the textual disclosure in over 1,000 issuance prospectuses from all asset-backed security (ABS) deals reported under the loan-level reporting initiative of the European Central Bank. Our results show that the quality and the quantity of textual disclosure, measured as the share of boilerplate language, the linguistic complexity, and the disclosure length, substantially influence investors' pricing at security issuance beyond all observable risk factors. An increase of the share of boilerplate language by one standard deviation lowers the demanded yield spreads by 17 basis points (bp), which represents about 18% of the mean initial yield spread of 91 bp in our sample. Moreover, investors' risk assessment is weakened if the ABS prospectuses are more standardized, complex, and longer because the yield spreads demanded by the investors at security issue are less predictive for future security performance. In line, we show that investors adjust their pricing during the security lifetime more strongly for securities with more complex and long prospectuses. Although this pricing behavior is not always to the disadvantage of investors, from a more general perspective, it is very detrimental for the effective functioning of securities

markets. Our results are not driven by the complexity of the underlying ABS transaction structure or the underlying collateral, nor do they depend on the law firms involved. Using a difference-in-difference regression, we show that the quality and quantity of textual disclosure in ABS prospectuses have homogenized after the introduction of new regulations. Our results have important implications for market participants and regulators alike, placing the quality and quantity of textual disclosure in prospectuses high on their agenda.

4 - The Relation between Environmental Awareness and Stock Returns
Andreas Oehler, Matthias Horn, Amal Dabbous, Alexandre Croutzet

This study aims to empirically assess if a measure of global environmental awareness can forecast stock returns. Further, it tests if stocks of more environmentally friendly companies are expected to show higher returns than those of less environmentally friendly companies when environmental awareness among investors increases. To capture environmental awareness, it uses the index of Dabbous et al. (2023) who identify 342 keywords and aggregate the individual Google search volumes of these keywords to construct a measure of environmental awareness. All aspects of the E-pillar in Environmental, Social, and Governance (ESG) rating provided by Sustainalytics are used to proxy how environmentally friendly companies are. Daily total return and market capitalization data from Thomson Reuters Datastream from the beginning of the year 2010 until the end of the year 2018 are used. In addition to the analysis with individual stock level data, we sort stocks based on their E-pillar score and form quintile portfolios for every month. We calculate the difference between the returns of the fifth quintile portfolio (highest E-pillar score) and the first quintile portfolio (lowest E-pillar score). Results confirm that on average, individual stocks with a higher E-pillar score show lower returns and alphas. Second, the findings indicate that when climate change concerns rise unexpectedly, stocks with higher E-pillar score reduce the differences in returns and alphas or show even higher returns and alphas than stocks with lower E-pillar score. The results confirm that when environmental issues matter, stocks with higher environmental risks suffer more than stocks with lower environmental risks.

■ FA-09

Friday, 8:30-10:00 - ESA O(st) 221

Continuous and Global Optimization

Stream: Continuous and Global Optimization
Invited session
Chair: *Sigifredo Laengle*

1 - Solving optimal design problems with mixed-integer convex methods
Deborah Hendrych

The Optimal Design Problem consists in picking a subset from potential experiments that allow us to maximize the information captured on the system. The Fusion problem is a variation of the standard problem where some experiments were already selected and the task is now to choose additional experiments. Both problems can be formulated as Mixed Integer Non-Linear Problems (MINLP). A measure of the information captured on the system is required for optimal design problems, we use the A- and D-optimal criteria, respectively. We compare different solving strategies for MINLP on randomly generated instances of the standard and fusion optimal design problem: Outer Approximation using the nonlinear objective to generate cuts on the underlying Mixed Integer Problem (SCIP), another Outer Approximation scheme based on a mixed-integer conic formulation and lastly a new Branch-And-Bound approach which uses a Frank-Wolfe-based algorithm to solve the nodes. We perform experiments on both information criteria and the standard and fusion variants, the results show that the last strategy is faster and more stable, especially for large instances.

2 - Inverse-optimization-based uncertainty set for robust linear optimization
Ayaka Ueta, Mirai Tanaka, Ken Kobayashi, Kazuhide Nakata

We consider solving linear optimization (LO) problems with uncertain objective coefficients. For such problems, we often employ a robust optimization (RO) approach by introducing an uncertainty set for the unknown coefficients. Typical RO approaches require historical data or prior knowledge of the objective function to define an appropriate uncertainty set. For example, the well-known ellipsoidal uncertainty set is defined by the mean vector and covariance matrix of the uncertain coefficients. However, such information may not always be available in practice. In this study, we propose a novel uncertainty set for robust LO problems that does not rely on prior knowledge of the unknown coefficients. Specifically, we assume to have a set of observations consisting of the parameters of the constraints and the corresponding optimal solutions to the LO problems. Under this situation, we define an uncertainty set for the unknown objective coefficients so that each observed solution belongs to the optimal solution set of the respective LO problems. We derive the explicit form of this uncertainty set as a polytope by applying techniques of inverse optimization (IO). We prove that the robust LO problem with the proposed uncertainty set can be equivalently reformulated as an LO problem, which is as tractable as the deterministic problem. We also show that our IO-based uncertainty set reduces as the number of observations increases. This is a natural property for uncertainty sets, although it is not necessarily guaranteed in previous studies. We evaluate the effectiveness of our proposed IO-based uncertainty set by numerical experiments.

3 - Structure-Aware Relaxation Selection for Quadratically Constrained Quadratic Programs
Buket Özen, Burak Kocuk

Quadratically constrained quadratic programs (QCQPs) are frequently encountered in optimization, appearing in fields such as OR, power systems, signal processing, chemical engineering, and portfolio theory. Although they are flexible in modeling real-world problems and there has been recent effort to comprehend their properties, non-convex QCQPs are difficult to solve in practice. Current approaches from literature typically rely on either Semidefinite Programming (SDP) or Linear Programming (LP) relaxations, with each working well for specific problems but not providing a complete understanding of others. This lack of understanding makes "structure-blind" general-purpose methods less effective than problem-specific solution approaches. The goal of this research is to provide a "structure-aware" relaxation selection process for non-convex QCQPs that can determine whether an SDP- or LP-based approach is more advantageous based on the instance structure. We state the research question as follows: How can one unravel the structure of an unknown QCQP instance to be SDP-favoring or LP-favoring, i.e., whether the SDP or the LP relaxation would produce the stronger bound without solving them? Our approach relies on theoretical exploration of the stylized problem instances by the effect of the spectral properties and sparsity pattern of the data matrices to the feasible regions of the aforementioned relaxations and utilizes a classification model that correctly predicts the category of a new instance (either SDP-favoring or LP-favoring).

4 - Calculation formula of the viability kernel in convex and linear dynamical systems
Sigifredo Laengle, Tomás Laengle-Aliaga

The most critical problem of viability theory is determining the initial states of a dynamical system for which at least one solution remains in the same set. This problem is analogous to many real situations, particularly management problems modelled as high-dimensional dynamic systems. However, the high dimensionality hampers the practical utility of the theory. The existing literature reports difficulties with models of more than four dimensions. Therefore, we investigate the current algorithms and propose a calculation formula for high-dimensional linear and convex problems. We also apply the solution to a management science problem. This paper presents a summary of our results. Doing the work, we find that our formulation is more efficient than existing algorithms. Our proposal facilitates the practical application of the determination of viable sets. Finally, since many dynamical systems are neither convex nor linear, extending our work to such systems is the immediate challenge.

■ FA-10

Friday, 8:30-10:00 - ESA W(est) 221

GOR Young Researchers Awards

Stream: PC Stream
Award Competition session
Chair: *Stefan Ruzika*

1 - The traveling salesman problem with drone resupply
Michael Dienstknecht

In search for ways to reduce delivery-induced road congestion, drones have become quite popular in the field of last-mile logistics. An abundance of concepts has been developed over the past few years - drones being launched from static infrastructure like (micro) depots, drones being launched from mobile devices like trucks, ships, trains or even flying warehouses. What all these concepts have in common, is the direct interaction between drone and customer as drones are used to actually deliver parcels to the customer's home. While this may work in some cases, it may not (or not satisfactorily) in others. For example, a customer may not be accessible to the drone due to lacking landing space or may make a point of personal interaction as part of the customer experience. An alternative still taking advantage of a drone is deploying it for re-supplying the actual delivery person from a distant depot. Thereby, we not only avoid direct drone-customer interaction, but also extend the delivery person's capacity and, moreover - and particularly valuable in dynamic quick-delivery applications -, enable re-supply on the road. We investigate such a delivery concept. Specifically, we define a prototypical problem setting as observed in practice, develop a mixed-integer programming formulation as well as heuristic solution procedures and analyze the concept's strengths and weaknesses in an extensive computational study.

2 - A Bilevel Optimization Approach to Decide the Feasibility of Bookings in the European Gas Market
Johannes Thürauf

The European gas market is organized as a so-called entry-exit system with the main goal to decouple transport and trading. To this end, gas traders and the transmission system operator (TSO) sign so-called booking contracts that grant capacity rights to traders to inject or withdraw gas at certain nodes up to this capacity. On a day-ahead basis, traders then nominate the actual amount of gas within the previously booked capacities. By signing a booking contract, the TSO guarantees that all nominations within the booking bounds can be transported through the network. This results in a highly challenging mathematical problem. Using potential-based flows to model stationary gas physics, feasible bookings on passive networks, i.e., networks without controllable elements, have been characterized in the recent literature. In this talk, we consider networks with linearly modeled active elements such as compressors or control valves. Since these active elements allow the TSO to control the gas flow, the single-level approaches for passive networks from the literature are no longer applicable. We thus present a bilevel model to decide the feasibility of bookings in networks with active elements. Exploiting a structural assumption for the active elements, we can equivalently reformulate the original bilevel model with a nonlinear lower-level problem such that the lower-level problem is linear for every given upper-level decision. Consequently, we derive several single-level reformulations for this case. The latter also lead to novel characterizations of feasible bookings in networks with active elements that do not lie on cycles. We compare the performance of our methods by a case study based on data from the GasLib.

■ FA-11

Friday, 8:30-10:00 - ESA H

Multi-objective optimisation in energy and environment

Stream: Energy and Environment
Invited session
Chair: *Michael Bucksteeg*

1 - Life-Cycle based Multi-Objective Investment Optimization for the longterm Planning of Energy Systems
Heidi Hottenroth, Ingela Tietze, Tobias Viere

As the world transitions to renewable energy systems, it is crucial to take into account both cost and environmental impacts. However, the focus on cost and climate indicators often overlooks the potential burden shifting to other environmental concerns. To address this issue, the decision support tool LAEND (Life cycle Assessment based ENergy Decision support) which combines energy system modelling and life cycle assessment has been developed. It follows a multi-period myopic optimization approach applicable at the level of residential quarters. The resulting investment and dispatch planning of (renewable) energy systems covers electricity, heat, and electric mobility by sector-coupling. Grid electricity is implemented with different electricity mixes and thus environmental impacts over time. The model minimizes total impacts, which are the sum of weighted and normalized economics and environmental impacts. In a case study, LAEND is applied to a residential neighborhood with mainly single family houses in southern Germany. The results show different system configurations depending on the optimization goal, with the solutions tending towards higher installed capacity with higher weights of climate impact and lower installed capacity with higher weights of costs. Thus, the decision maker needs further support in order to choose a sound transformation path considering different environmental goals. The multi-criteria optimization, which combines environmental and cost criteria, reveals a system configuration that compensates for the different objectives. In conclusion, LAEND provides a decision support tool for optimizing energy systems that considers the environmental footprint and costs simultaneouslyto prevent burden shifting.

2 - A multi-criteria assessment framework for direct load control in residential buildings from an occupants' perspective
Paul Fabianek, Constanze Liepold, Reinhard Madlener

Based on economic and occupants-relevant criteria, this paper proposes an assessment framework for direct load control (DLC) approaches, using the Analytic Hierarchy Process approach for a Multi-Criteria Decision Analysis. For DLC, as a form of demand response, a third party provider (e.g., grid operator, aggregator) is allowed to control or limit the residential load after sending a control signal. The evaluation of different DLC approaches from a residential perspective can be done transparently using our assessment framework. The relevant criteria for the evaluation were derived from literature. Five criteria were found to be particularly relevant for the evaluation of DLC approaches: frequency and duration, control, financial compensation, transparency, and guaranteed comfort. The assessment framework includes value scores, which represent the degree to which a specific DLC approach meets a given evaluation criterion and combines them with the criteria weights derived in the Analytic Hierarchy Process. The results indicate the particular importance of the avoidance of loss of comfort and control. The framework seems useful for grid operators, aggregators, and policy makers that need to find ways to design and implement demand response measures in the private household sector that are acceptable to occupants.

3 - Investigating Energy Scenarios from the Stakeholders' perspective with MCDA
Matthias Grajewski, Stefan Vögele, Imke Rhoden, Dirk Rübbelke

Any transformation of the energy system, which can be particularly challenging, requires the support of a significant part of stakeholders. Having a set of possible scenarios and measures for transformation identified, it is necessary to identify the stakeholders' attitude towards these scenarios and corresponding measures. However, processes for considering stakeholders' perspectives like e.g. surveys are usually very time-consuming and costly. Moreover, it is challenging to reflect modifications in the scenarios as if survey results on scenarios can no longer be related to their modifications, a new process of investigating the stakeholders' attitudes may be required. In our talk, we show how multi-criteria decision analysis (MCDA) can be employed for analyzing the stakeholders' possibly diverging attitudes toward options for transforming the energy system. We provide a flexible template for analyzing stakeholder preferences toward transition paths. This flexibility comes from the fact that our MCDA-based approach does not involve intensive empirical work with stakeholders. Instead, it involves subjecting assumptions to robustness analysis, which can help identify options to influence stakeholders' attitudes toward transitions. We present an approach to robustness analysis based on geometrical properties of the MCDA model, Promethee II, but can be applied to a large class of MCDA models. Modeling MCDA parameters as probability distributions enables robustness analyses, incorporating inhomogeneity of stakeholders, and allows merging with other sources of information, e.g. surveys. We apply our method on the transition to different possible energy scenarios.

4 - A solution approach for the Green Multi-Objective Flexible Job Shop Scheduling Problem with energy storage systems
Sascha C Burmeister, Daniela Guericke, Guido Schryen

Environmental sustainability has become increasingly important in recent years, as many countries set targets to reduce the carbon emissions. A major consumer of energy is the manufacturing industry. For manufacturers it is essential to find ways to align their production with the current energy mix and consume energy at times with high renewable energy production without jeopardizing production deadlines. In addition to schedules based on the energy mix, energy storage systems can be used to compensate for fluctuations in renewable energy sources. In the literature, the Green Flexible Job Shop Scheduling Problem (FJSP) is concerned with resource and environmental aspects in addition to the economic objective of the minimum makespan. However, existing approaches neglect the volatile dynamic energy mix, a multi-criteria objective, or the consideration of modern energy storage systems. We aim to close this research gap and propose an algorithm based on the Non-dominated Sorting Genetic Algorithm (NSGA-II) with the goal of minimizing both, makespan and emissions. In order to design low-emission production, the algorithm constructs production schedules while considering the charging and discharging of an energy storage system. We evaluate the approach in computational experiments using prominent FJSP-benchmark instances from the literature with real emissions. We investigate the trade-off between a short makespan and low carbon emissions based on solutions on the approximated Pareto front and discuss the value of energy storage systems for sustainable production.

■ FA-12

Friday, 8:30-10:00 - ESA K

Quantum Optimization

Stream: Simulation, Reinforcement Learning and Quantum Computing
Invited session
Chair: *Friedrich Wagner*

1 - Combining Quantum Algorithms and Integer Programming for Maximum Cut

Friedrich Wagner, *Frauke Liers*

To date, quantum computation promises potential for improved heuristics in combinatorial optimization. However, when aiming for global optimality, one has to rely on classical exact methods like integer programming. State-of-the-art integer programming algorithms can efficiently compute relaxations even for large instances, but may have to enumerate a large number of subproblems for determining an optimum solution. If the potential of quantum computing realizes, it can be expected that in particular finding good solutions for large problems can be done fast. Still, near-future quantum hardware considerably limits the size of treatable problems and is also prone to noise. In this work, we go one step into integrating the potentials of quantum and classical techniques for combinatorial optimization. We propose a hybrid quantum-classical heuristic algorithm for the maximum cut problem on weighted graphs. The algorithm relies on a classical linear programming relaxation, making it particularly well-suited for integration into an exact integer programming framework. For instances that are too large to be handled by quantum machines directly, we reduce the problem size according to the solution of the linear programming relaxation. As a result, the reduced problem can be solved by quantum computers of limited size. Returned solutions are extended to feasible solutions of the original instance. Moreover, we improve the applicability of QAOA, a well-known parameterized quantum algorithm, by deriving optimal parameters for special instances of the weighted maximum cut problem which motivates a parameter estimate for arbitrary instances. We present numerous computational results from real quantum hardware for instances with up to 100 nodes.

2 - On the influence of a quantum annealer in a hybrid optimization framework for solving a high-throughput scheduling problem

Tobias Seidel, *Dominik Leib*, *Abhishek Awasthi*, *Michael Bortz*, *Raoul Heese*

The standard approach to solve larger discrete optimization problems with quantum hardware is to apply a hybrid framework. A part of the computations is performed on classical hardware and suitable subproblems are solved on the quantum hardware. In this work we are particularly interested in the impact of the D-Wave quantum annealer when solving the problem within the hybrid algorithm. As an example, we study a scheduling problem motivated by an industrial application in a high-throughput laboratory. The problem consists in processing a given set of samples as fast as possible. As the limiting resource there is a robot that must transport the samples from station to station in the laboratory. We model the problem as a QUBO. We then solve the problem using the typically implemented hybrid workflow. Within the hybrid solver we replace the quantum annealer by simulated annealing and compare the results. We find that the quantum annealer for the considered example is not clearly superior to the simulated annealer but can improve a local search with suitable perturbations.

3 - A case-based comparison of three key quantum approaches to discrete optimization.

Alexey Bochkarev, *Raoul Heese*, *Sven Jäger*, *Philine Schiewe*, *Anita Schöbel*

An important potential application for quantum computing is speeding up the solution of optimization problems. Currently, there are several fundamentally different types of quantum processing units, which entails a spectrum of possible approaches to tackle an optimization problem. The variety of methods and hardware, along with the inherent complexity of quantum science, makes it relatively difficult for operations research scientists to leverage the emerging quantum computing technology. In this work, we aim to provide a hands-on comparison of key classes of quantum optimization technologies and point out the main corresponding methodological challenges. Starting with a classical optimization problem such as the traveling salesperson problem, we discuss and contrast possible ways to solve it using present-day quantum hardware with its significant inherent limitations. Specifically, we consider quantum annealers, general gate-based quantum computers (in the context of variational quantum algorithms, such as QAOA), and Rydberg atom-based devices. We first outline the high-level methodological stack of quantum optimization, i.e., the key steps involved in solving the problem, including problem reformulations, steps involving pre- and post-processing, coordination between the classical and quantum processing units, and quantum-specific calculations. We show that these key steps strongly depend on the respective quantum hardware and present a uniform framework that allows us to compare the main hardware restrictions and methodological issues: the required number of qubits, dealing with their connectivity, and designing a computational pipeline with a reasonable level of hardware-related errors.

■ FA-13

Friday, 8:30-10:00 - ESA W(est) 121

Electric busses

Stream: Mobility and Traffic
Invited session
Chair: *Philip de Bruin*

1 - Scheduling Electric Buses with Stochastic Driving Times

Philip de Bruin, *Marjan van den Akker*, *Han Hoogeveen*

We study the Stochastic Electric Vehicle Scheduling Problem and focus on electric buses. We want to minimize the cost of operation, taking into account the battery life. Our goal is to make our schedules more robust against delays caused by, for example, various traffic conditions, or passenger loads. In order to make our schedules more robust against these delays, we work with stochastic driving times instead of deterministic driving times.

To solve the resulting optimization problem, we use a combination of simulated annealing and simulation. Because of the stochastic driving times, we use simulation to calculate the cost of a solution. This, however, comes with a performance penalty. Thus, we investigate different methods of determining how many simulation runs are needed, such that we still make a correct choice about which solution is better. The techniques we consider here are: Optimal Computation Budget Allocation, Indifference Zones, and a method we developed ourselves, which uses t-tests.

We show that the use of our t-test method or Indifference Zones increase the runtime performance while performing similar in terms of their final score. Furthermore, when using stochastic driving times, we see in increase in the punctuality of the buses. However, we also see a slight increase in operating cost.

2 - Scheduling Inductive Charged Passenger Buses on Airport Aprons: A Numerical Study

Niklas Pöch

Given the increasing importance of sustainability in the aviation sector due to climate change, electrifying ground vehicles on airport aprons is one way to reduce emissions. Dynamic inductive charging, which wirelessly charges vehicles while moving, is especially suitable for airport apron vehicles as it eliminates downtime for charging electric vehicles compared to conductive charging. We focus on scheduling electric passenger buses on airport aprons that use an inductive charging infrastructure to charge their batteries. Specifically, we investigate which vehicle should perform each service trip, whether it is transporting passengers from a gate to an airplane or from an airplane to a gate. We aim to ensure the reliable operation of these buses and avoid delays and breakdowns due to empty batteries. We present a formulation of the problem using a mathematical model and describe our ongoing numerical study and its initial results.

3 - Multi-period planning for electric bus systems under simultaneous optimization of vehicle schedules, charging infrastructure, and fleet composition

Miriam Stumpe, David Rößler, Guido Schryen, Natalia Kliewer

In light of the worldwide initiatives aimed at reducing emissions and decreasing dependence on fossil fuels, public transport operators are under increasing pressure to not only substitute internal combustion engine (ICE)-buses with electric buses but also to establish a corresponding charging infrastructure. Numerous European cities have taken the first steps towards shifting from ICE-bus transportation to electric bus systems. To scale these efforts, it is crucial to develop cost-efficient gradual expansion plans by means of multi-period planning. While strategic planning, such as the deployment of charging station infrastructure, has been the primary focus of many studies on the transition to electric bus systems, relatively few have addressed the operational aspects. Specifically, previous analyses lack on strategic aspects regarding the adaption of vehicle schedules for electric bus systems. We contribute to closing this research gap by proposing a new mathematical formulation for the multi-period transformation process towards electric bus systems under simultaneous optimization of vehicle schedules, charging infrastructure, and fleet composition. To this end, we extend a previous MILP model by including the aspects of fleet mix and multi-periodicity - minimizing the total cost of ownership comprising fleet, charging equipment, and operational cost. Using real-world problem instances, we evaluate the extent to which the new formulation is solvable by commercial MIP-solvers within acceptable time limits and explore alternative (heuristic) solution methods.

4 - Non-linear Battery Behavior in Electric Vehicle Scheduling Problems

Fabian Löbel, Ralf Borndörfer, Steffen Weider

The emergence of battery-powered electric vehicles in logistics and public transport settings complicates the well-studied vehicle routing or scheduling problem. Limited driving ranges and long refueling duration compared to combustion powered counterparts have to be considered for finding optimal vehicle schedules. Feasibility of solutions is dictated by the complex and non-linear battery behavior and its proper inclusion in models is still an open problem. We examine the emerging state of the art approach to modeling non-linear battery behavior in electric vehicle scheduling problems.

■ FA-14

Friday, 8:30-10:00 - ESA W(est) 120

Network design

Stream: Mobility and Traffic
Invited session
Chair: *Philine Schiewe*

1 - Network design for urban transit systems with hybrid transportation units

Paul Bischoff, Benedikt Lienkamp, Maximilian Schiffer

The concept of cargo hitching using hybrid transportation units (HTUs) presents a promising solution to address the underutilization of public transportation systems (PTSs) during off-peak hours while simultaneously reducing the externalities of urban freight distribution. By integrating freight transportation into existing PTSs, municipalities can optimize their resources, reduce congestion, and diminish the impact of conventional freight transportation on the road network. Here, HTUs, designed to transport passengers or freight by leveraging a flexible interior, allow the transformation from existing passenger-only concepts to integrated PTSs. Against this background, we study a capacitated network design problem to enable cargo-hitching in existing PTSs. More specifically, we study a setting with fixed vehicle routes and timetables in which vehicles can be equipped with HTUs to enable cargo-hitching. In addition to routing freight, we explicitly consider passenger routing to ensure a high passenger service level and quality. We optimize the network design from a total cost perspective to account for network design costs tied to the investment in HTUs, and freight routing costs. We show how to reduce the resulting network design problem's complexity by encoding some of its constraints in a spatially and temporally expanded layered graph. We present a mixed-integer linear program to solve the resulting network design problem. Moreover, we present an exact branch and cut algorithm that allows us to solve instances of realistic size and to analyze a case study based on the subway network in the city of Munich to derive managerial insights.

2 - Determining the Stops and Ring Routes of the Suburban Train Line: An Alternative Transportation for Industrial Workers

Eren Özceylan

Gaziantep, a city in the South Anatolia of Türkiye, has seven organized industrial zones and is the fifth largest exporting province. Every day, 250 thousand workers commute from the city center to the industrial zones in order to provide the necessary manufacturing in the factories. The largest part of this transportation is provided by approximately 2500-3000 shuttles. It is clear that traffic jams, air pollution, and other negative effects caused by shuttles have become an unbearable burden for the city. In order to solve these problems, there is a suburban train line project to go from the city center to the organized industrial zones, and the workers are requested to provide their transportation by using this train line. Therefore, where will be the locations of the stops on the train line and on which routes the rings that will feed these stops will travel are some of the questions that need to be answered. Within the scope of this study, the locations of the stops on the train line will be determined upon the request of Gaziantep Municipality and which stops will be fed by ring services. For this purpose, a three-stage solution approach will be applied. In the first stage, the addresses of the workers will be written on the map (using Esri ArcGIS) over the pilot region in order to see the demand intensity. In the second stage, the potential stops will be evaluated (using maximum coverage location) according to the maximum number of covered workers. In the last stage, ring routes (considering capacitated vehicle routing problem) will be determined taking into account the selected stops. The results to be obtained and different scenarios will be presented to Gaziantep Municipality as a policy developer.

3 - Strengthening the sustainable transport network by optimizing mobility hub locations

Vladimir Stadnichuk, Laura Merten, Christian Larisch, Grit Walther

Mobility hubs facilitate the comfortable transfer between different means of transport, and thus represent an important element for strengthening the transport network. However, the optimal location of mobility hubs challenges municipalities and mobility service providers due to the complexity of urban structures and the need to anticipate changes in travel behavior. Against this background, we present an interdisciplinary approach to create a more sustainable transport network by determining the optimal locations for mobility hubs from the perspective of a municipality. We first pre-select potential locations using a transport planning approach based on a travel demand model. Afterwards, we select optimal hub locations from these potential locations based on a bilevel optimization model, which represents the underlying hierarchical structure. Herein, the upper level represents the municipality that is deciding where to locate mobility hubs based on expected users' travel behavior and external costs. The lower level represents the users of the urban transportation network that adapt their travel behavior to the new means of transport at the mobility hubs, and thereby influence the decisions of the municipality. We validate our approach on a case study for the city of Aachen, Germany. Initial results show that mobility hubs can increase the share of multimodal trips and

substitute trips with private cars. However, we also find that the overall share of multimodal trips remains low, even with optimally located mobility hubs. The next steps are to analyze different scenarios, e.g., the impact of the introduction of free public transport, and to incorporate an urban planning perspective to assess the structural feasibility of mobility hubs at the selected locations.

4 - The Bus Rapid Transit Investment Problem
Philine Schiewe, Evelien van der Hurk, Rowan Hoogervorst, Anita Schöbel, Reena Urban

Bus Rapid Transit (BRT) systems can provide a fast and reliable service to passengers at lower investment costs compared to tram, metro and train systems. Therefore, they can be of great value to attract more passengers to use public transport. This paper thus focuses on the BRT investment problem: Which edges (segments) of a single bus line should be upgraded such that the number of newly attracted passengers is maximized? Motivated by the construction of a new BRT line around Copenhagen, we consider a setting in which multiple parties are responsible for different segments of the line. As each party has a limited willingness to invest, we aim to quantify the trade-off between the number of attracted passengers and the total investment budget to assist decision making. We consider two potential passenger responses to upgrades on the line, and, to prevent scattered upgrades along the line, we allow restrictions on the number of connected components to be upgraded. We propose an epsilon-constraint based method to enumerate the complete set of non-dominated solutions and investigate the complexity of this problem. Moreover, we perform an extensive experimental evaluation on artificial instances and on a case study based on the BRT line around Copenhagen. Our results show that we can generate the full Pareto set for real-life instances and that the resulting trade-off between investment budget and attracted passengers depends clearly on both the OD demand and passenger response to upgrades. Moreover, we show how the found Pareto plots can facilitate the comparison of line alternatives in our case study.

■ FA-15

Friday, 8:30-10:00 - R 0077, VMP5

Simulation in Health Care

Stream: Health Care Management
Invited session
Chair: *Christina Büsing*

1 - Effects and performance analysis of bed reservations for specific departments in a surgical intensive care unit using discrete-event simulation
Robin Schlembach

Intensive care units (ICUs) are specialized departments designed to provide comprehensive care and continuous monitoring to critically ill or injured patients. These units are equipped with high-tech medical equipment and staffed by specially trained healthcare professionals. Due to their high cost and limited capacity, ICUs often pose a bottleneck in the patient flow, making efficient use of ICU resources a critical concern for both hospitals and patients. Especially hospital departments with a high proportion of intensive care patients do sometimes express the wish to reserve ICU beds exclusively for their patients. This reservation policy can be a source of debate and controversy, as it can affect the overall performance of the ICU. To investigate the advantages and disadvantages of such a policy, this study first develops a discrete-event simulation model of the current patient flow in an ICU based on real-world data from a Bavarian maximum-care hospital. On this basis, the effects of bed reservation for certain departments will be analyzed in a scenario as well as the impact on the overall performance of the ICU to provide decision support in this regard. We show that reserving capacity for specific units results in benefits for them at the expense of performance losses for the whole system. In our sensitivity analysis, we are able to quantify these effects.

2 - Stochastic Vaccine Scheduling and Inventory Planning for COVID-19 Vaccination
Elvin Coban

The World Health Organization declared the new Coronavirus a pandemic in 2020, and countries worldwide have been taking rigorous measures to contain its spread. One of the most crucial steps was to rapidly administer the developed vaccines, but the challenges of storage and transportation made vaccine distribution planning difficult. For instance, the Pfizer-Biontech vaccine, one of the most widely used vaccines, requires a cold chain, which made scheduling more complex. In this study, we propose a simulation-optimization approach for stochastic vaccine scheduling and inventory planning, taking into account the uncertainty of vaccine and patient arrivals. Our objective is to minimize the expected cost of wasted vaccines and missed doses (when a patient is not vaccinated twice) by using thermal shipping containers instead of ultra-cold storage units.

3 - Online Appointment Assignment with Time Windows
Mariia Anapolska, Christina Büsing

In this talk, we consider the problem of assigning patients online to appointment slots of unit length. The problem statement is motivated by applications in outpatient healthcare, particularly in elective surgery, where it is common to assign appointments in an online manner to patients with different levels of urgency. In our setup, the number of slots per day is known in advance. Patients arrive online and are characterized by a time window, in days, within which they need an appointment. Patients are assigned immediately upon arrival. Previous patients can be reassigned, if otherwise the current patient could not receive a feasible slot. Simultaneously, as the time passes, the slots perish, i.e. cannot be assigned any longer. If despite reassignments a patient cannot be scheduled, she is rejected. The goal of the Online Appointment Assignment with Time Windows (Online AATW) is to minimize the number of deferrals and the number of perished slots, thus maximising the utilisation of the system's capacity. We provide a formalisation of Online AATW and relate it to existing literature on online matching and assignment problems. Moreover, we simulate arrivals of different patient types (regular and urgent) and compare scheduling strategies from the literature on these inputs.

■ FA-16

Friday, 8:30-10:00 - R 0079, VMP5

Deployment Frameworks

Stream: Software for OR
Invited session
Chair: *Alexander Biele*

1 - Demonstrating Business Impact of Operations Research and Machine Learning Models conveniently with Xpress Insight
Alexander Biele

Operations Research (OR) applications suffer from not being able to quickly show the business impact in an integrated manner. This reduces the number of OR and their general acceptance applications in an industrial environment. Most of the development time is spent on developing optimization models, tuning their parameters, and finessing textual output into slides for an appealing presentation. Quickly demonstrating business impact of different scenarios in an automated way or even integration in an enterprise software system is out of reach since adding attractive user interfaces or integration in enterprise application is very time consuming and costly. On top of that, scientists, even computer scientists, are not necessarily the best choice for building and maintaining such software. We will demonstrate how to reduce the development cycle, from model implementation, scenario analysis until closing the feedback loop with business users with FICO Xpress Insight at the example of selected examples for production planning and scheduling. Xpress includes a web deployment platform, Xpress Insight, enabling solution developers, data scientists, and OR experts to rapidly develop and deploy applications without needing to be a JavaScript or html expert. We will demo how a Python model can be converted into a user-friendly app via drag & drop within a few minutes.

2 - Optimizing Agriculture in the Cloud: A Real-Life Example of Model Deployment with GAMS MIRO
Robin Schuchmann

With the evolution of software and hardware, the way optimization software is used has changed significantly. Today, users prefer logging into online services to perform their optimization on centralized compute resources. These trends do not stop at GAMS, and in recent years, various new developments have been initiated to meet the changing requirements. In this talk, a real-life example in cooperation with the

Leibniz Centre for Agricultural Landscape Research (ZALF) is used to show what a modern software solution with GAMS looks like. We will explore the deployment of a GAMS model using GAMS MIRO, a powerful tool for creating a graphical user interface that can be run in cloud environments. The model (Multi Objective Decision support tool for Agro ecosystem Management - MODAM) is a Bioeconomic whole farm model that supports agricultural land users in decision making on optimal resource allocation. It generates optimal production patterns and a number of economic and ecological indicators. From modeling, to visualization, to integration into existing IT infrastructure - real-world applications like these have many aspects. We will discuss how to efficiently organize projects and work around obstacles during the continuous development process by adapting to changing requirements until the application achieves its intended goals.

3 - Enterprise Optimization Software - Rapid Development
Jens Peter Kempkes, Ingmar Steinzen, Stefan Bunte

How to develop enterprise optimization software rapidly? What functional and cross-functional features (such as scenarios, user-management, logging, ...) are required. How to extract, transform and load external data, how to validate massive data sets? How to present results human understandable? How to scale well and affordable? Let's discuss some answers.

4 - LocalSolver Studio: a platform for optimization prototypes and applications
Julien Darlay

LocalSolver Optimizer is a global optimization solver that combines exact and heuristic methods to find near-optimal solutions in minutes. LocalSolver Studio is a web application released in 2023 and built on top of LocalSolver Optimizer. It includes a code editor to write and debug optimization models and a graphical interface to visualize solutions. Model generators for routing and scheduling have been integrated to build a first model in just a few clicks. The generated model can be tuned to included specific business constraints and objectives using our modeling language. Dedicated widgets allow users to display tours on a map or activities on a Gantt chart. The optimization is done remotely on dedicated servers with the latest version of LocalSolver Optimizer. In this talk we will give a demo of LocalSolver Studio and show how it can be used in industry or for teaching.

■ FA-17

Friday, 8:30-10:00 - ESA O(st) 121

Integer programming for polynomial optimization

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Matthias Walter*

1 - Product and factor filtering for the Reformulation-Linearization Technique for bilinear and mixed-integer problems
Ksenia Bestuzheva, Ambros Gleixner, Tobias Achterberg

The Reformulation-Linearization Technique (RLT) is a method for constructing cutting planes for mixed-integer and polynomial optimization problems. RLT yields tight linear programming relaxations, but its efficiency is often hindered by the high cost of separation and the large sizes of resulting linear programs. In this talk we present our RLT cut generation framework. First, we show how to derive bilinear product relations from mixed-integer linear constraints with at least one binary variable, thus providing a new way of leveraging the strength of RLT relaxations. Second, we present an efficient RLT cut separation algorithm for both derived and original product relations. This algorithm considers only a subset of variable and constraint combinations, producing relaxations of the same strength with lower computational cost of the separation. Finally, we present a technique for filtering implicit products based on evaluating their non-redundancy with respect to variable domains and the constraints they are derived from. We present an extensive computational study performed with SCIP and Gurobi.

2 - On Some Theory and Practice of Odd-Cycle Separation for MaxCut and QUBO
Sven Mallach

We present structural results on odd-cycle inequalities, their correspondence to parity constraints in terms of XOR relations on boolean variables, and some effects of cycle chordalizations. We also address how to turn these insights into practical advances in terms of modeling and separation.

3 - Hypergraphs, polyhedra and algorithms for polynomial optimization
Matthias Walter, Alberto Del Pia

Mixed-integer nonlinear optimization problems involving polynomials can be reformulated by creating an auxiliary variable for every monomial and convexifying the product constraint of each such variable. This gives rise to multilinear polytopes. In the talk I will describe this relationship, summarize what is known about these polytopes, and then focus on known inequalities classes. The emphasis will be on separation algorithms in order to use these inequalities as cutting planes. Finally, I will present some insights from a prototype implementation. The presented new results are joint work with Alberto Del Pia.

4 - On the cubic correlation clustering polytope
Silvia Di Gregorio

In this work, we study the cubic correlation clustering problem from a polyhedral point of view. Several heuristics for applications in computer vision have been recently developed. We start by providing an integer linear programming formulation, and study its basic properties. Next, we introduce three additional classes of facet-defining inequalities and discuss methods to separate them.

■ FA-18

Friday, 8:30-10:00 - ESA O(st) 122

Combinatorial Optimization III

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Christoph Geis*

1 - On the Covering of Trees with Short Paths
Christoph Geis, Sven Krumke

The set cover problem is a well-studied problem in combinatorial optimization. Given a finite ground set U and a collection S of subsets the problem is to determine a minimum size (or cost) subset of S such that each element from U is contained in at least one of the chosen sets. The set cover problem is known to be NP-hard and hard to approximate. In this paper we study the complexity and approximability of the problem when we are given additional structural restrictions on the sets in the collection S. More precisely, we consider the problem of covering the nodes of a tree with a minimum-cost selection of paths from a given family of paths. We tackle the problem in a multi-set-multi-cover setting, which means that given a tree T with demands on the vertices and a family P of paths in T with non-negative costs as well as capacities, we are tasked to find a multisubset of P of minimal costs such that every vertex from the tree is contained in enough chosen paths to cover their given demand. We call refer to this problem restricted to paths of length at most k and demands at most l as MCCPMCT(k, l). We give an almost complete characterization of the complexity of the problem MCCPMCT(k, l), the only open case being the case where k equals 3 and l equals 1. Moreover, we provide approximability and in-approximability results.

2 - Bipartite Hypergraph Perfect Matching Polytope
Elad Shufan, Hagai Ilani, Lior Aronshtam

Motivated by a tenant-plot assignment problem with couples, we investigate polyhedral issues regarding bipartite hypergraph matching. The assignment problem is the problem of assigning plots to tenants in a project of a purchasing group. When there are n tenants and n plots, and each tenant has a set of accepted preferred plots, the problem is a classical matching problem. The problem becomes NP-hard when some tenants join together in pairs to jointly choose pairs of acceptable plots. We model the tenant-plot assignment problem with couples as a bipartite hypergraph matching problem. Unlike bipartite graphs, a bipartite hypergraph can contain odd cycles. One of Edmond's theorems regarding matchings in graphs states that the matching polytope

of a graph is characterized by the set of vertices constraints and odd set constraints. We study possible analogues of this theorem for a bipartite hypergraph matching polytope. Another theorem of Edmond for graphs states that the coordinates of vertices of the fractional perfect matching polytope have values 0, 0.5 or 1 and the coordinates with value 0.5 correspond to disjoint odd cycles of the graph. This is no longer true for bipartite hypergraphs; We show examples where the fractional perfect matching polytope contains vertices with fraction coordinates other then 0.5.

3 - Bin Packing Problem with Conflicts and Item Fragmentation
Ali Ekici

In this study, we analyze a variant of the well-known Bin Packing Problem where items can be fragmented and some pairs of items cannot be packed into the same bin due to conflicts. The goal is to pack a given set of items into a minimum number of fixed-capacity bins while not packing fragments of conflicting items into the same bin. This problem is called the Bin Packing Problem with Conflicts and Item Fragmentation. It has applications in the delivery of items that cannot be transported in the same vehicle and load balancing in parallel processing where jobs can be split up. We develop a lower bounding scheme based on identifying a maximal clique of the conflict graph for the problem and propose a heuristic algorithm called the Sequential Maximum Degree Packing Heuristic which sequentially packs the items starting from the highest degree item using a mixed-integer model. We test the proposed solution approach on the instances with random conflict graphs and compare its performance against that of the benchmark algorithms in the literature. We observe that our approach outperforms the benchmark algorithms especially when the conflict graph is dense. It provides solutions with up to 13% less optimality gap compared to the algorithms in the literature. Finally, the proposed lower bounding scheme improves the trivial continuous lower bound only if a large maximal clique of the conflict graph can be identified. More specifically, we observe that the maximal clique based lower bounding scheme provides an improvement if the ratio of the size of the maximal clique to the number of items is above 0.3.

■ FA-19

Friday, 8:30-10:00 - ESA O(st) 123

About Secretaries and Prophets

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Daniel Schmand*

1 - Prophet Inequalities over Time
Elias Pitschmann, Andreas Abels, Daniel Schmand

We introduce an over-time variant of the well-known prophet inequality with i.i.d. random variables. Instead of stopping with one realized value at some point in the process, we decide for each step how long we select the value. Then we cannot select another value until this period is over. The goal is to maximize the expectation of the sum of selected values. We describe the structure of the optimal stopping rule and give upper and lower bounds on the prophet inequality. In online algorithms terminology, this corresponds to bounds on the competitive ratio of an online algorithm.

We give a surprisingly simple algorithm with a single threshold that results in a prophet inequality of approx. 0.396 for all input lengths n. Additionally, as our main result, we present a more advanced algorithm resulting in a prophet inequality of approx. 0.598 when the number of steps tends to infinity. We complement our results by an upper bound that shows that the best possible prophet inequality is at most the inverse of the golden ratio, which is approx. 0.618.

2 - Optimal algorithms for k-Secretary with biased evaluations
Ruben Hoeksma, Andres Cristi, Wouter Fokkema

In the k-secretary problem, we are tasked with making k selections from a set of n candidates arriving sequentially in a uniformly-at-random order. We consider the k-secretary problem where the candidates are partitioned into c groups that are mutually incomparable. This model is used to reflect the possibility that whatever evaluation method is used may have a (unknown) bias towards candidates with different backgrounds. By not comparing candidates of different groups, we prevent such bias from playing a role in the selection process. We exhibit optimal dynamic-programming-based algorithms for the problem with finite and infinite n (the limit model) and show several properties of these algorithms. In particular, we show that the optimal algorithm for the limit model has a simple and natural structure, and captures the worst-case guarantee for fixed c and k. This allows us to provide computational lower bounds on the competitive ratios for different values of c and k. Finally, we compare the performance of several simple algorithms to the optimal algorithm.

3 - Stackelberg Vertex Cover
Lennart Kauther, Katharina Eickhoff, Britta Peis

Stackelberg games are used to capture situations in which a dominant party called the leader first makes a decision and afterward, the other players called followers react to the leader's decision. A Stackelberg Vertex Cover game is played on an undirected graph G with weighted vertices. The leader controls some of the vertices and can thus determine their weight. The other vertices - e.g, representing competing offers - have a fixed weight. After the remaining weights have been set by the leader, the follower selects a minimum weight vertex cover. That is, a subset of vertices C such that C has minimum weight and every edge of G has at least one endpoint in C. The problem "Stackelberg Vertex Cover" (StackVC) describes the leader's optimization problem to select prices in the first stage of the game so as to maximize her revenue, which is the cumulative price of all vertices under her control that are contained in the follower's solution. Previous research showed that StackVC is NP-hard even when the underlying graph is bipartite. Yet, in the special case where all priceable vertices are on the same side of the bipartition, it was shown to be solvable in polynomial time. In search of the problem's complexity boundary, we examined the problem on paths. While we are able to provide an algorithm with polynomial - in fact even linear - time and space complexity, it is highly involved and builds on a meticulous analysis of the problem's structure.

■ FA-20

Friday, 8:30-10:00 - ESA W(est) 119

Human-Algorithm Interaction

Stream: Game Theory and Behavioral Management Science
Invited session
Chair: *Christian Jost*

1 - Points and Cards - A behavioral view of the decision-making under pull and push inventory policies.
Alexander Daniels, Guido Voigt

Whether and why pull inventory policies seem to outperform push inventory policies is a topic of discussion for decades. While some try to explain the difference through work-in-progress capacity limits or a higher degree of awareness when it comes to their supply chains after implementing a pull policy this paper tries to shed light on the behavioral impacts on decision-making. This paper investigates inventory decisions under "pull" and "push" inventory policies with stochastically normal distributed demand, lost sales, and periodic review cycles. To test the underlying theories a laboratory experiment with 60 participants was conducted. Two mathematically similar inventory policies are used. On one hand, Kanban represents pull and on the other hand a reorder point quantity policy represents the push side. The findings show significant differences in decisions making between the two policies. Decisions made in Kanban create lower order quantities but higher reorder points than those made under the reorder point quantity policy. The difference in decision parameters leads to different cost structures under the respective policies.

2 - Human-AI Collaboration: Advising the Crowd
Andreas Fügener

We examine how advice from an AI algorithm should be provided to decision-makers that work in a crowd setting. With a theoretical model and numerical experiments we show that the harmful effect of incorrect advice relative to the beneficial effect of correct advice increases with increasing crowd size. Thus, for larger crowds, more advice should be withheld so that it does not negatively affect the crowd accuracy.

We propose a mechanism for AI advice personalization that takes the crowd size into account.

In an experimental study where subjects classified images, we demonstrate that the crowd size-dependent advice personalization reduces the detrimental effects of incorrect advice and leads to an increase in crowd accuracy.

3 - Roles of AI in Collaboration with Humans - Automation, Augmentation and the Future of Work
Dominik D. Walzner, Andreas Fügener

The future of work will be characterized by a growing influence of artificial intelligence (AI). Human decision-makers may see significant changes in their day-to-day work as collaboration between humans and AI will likely become more common. In this collaboration, several roles can be simultaneously envisioned for AI.

This work explores the value of AI as a worker (i.e., performing tasks) and as an advisor (i.e., advising humans) in collaborative environments. We formalize the roles an AI could perform within an analytical framework, where the AI and (crowds of) humans work on a set of categorical decision tasks. We discuss the potential of different AI roles using numerical analyses and validate the results with an experimental study. Our main results demonstrate the relative strength of the AI roles: When between-task complementarity is high, the AI taking on the role of the worker is more promising than taking on the role of the advisor, while this relationship flips when between-task complementarity is low. When the AI simultaneously as worker and advisor, we see an interesting distribution of work pattern: The AI works on relatively easy tasks and provides advice for tasks where the performance of humans and AI are similar. Relatively difficult tasks are performed by crowds of humans without the AI. The AI therefore takes over tasks from humans so that they can work on more value-adding tasks, which leads to significant performance gains.

Our work provides several contributions to theory and practice. Our analytical framework can help to evaluate several human-AI collaboration types, and our results provide insights on the future of work.

4 - Improving Agents' Routing Performance with Algorithmic Nudging
Christian Jost, Sebastian Schiffels, Rainer Kolisch, Maximilian Schiffer

In today's gig-economy, many companies rely on self-employed agents to perform services at customer locations. Thereby, labor protection laws ensure that these companies do not exert a level of control over their self-employed agents that implies a de facto employer-employee relationship. As a consequence, companies limit their influence on the agents' operative planning and provide them only with the necessary customer-to-agent assignment, needed to perform the customer visits. For companies that reimburse their agents' travel cost this creates a dilemma. Here, companies benefit significantly, if their agents construct cost-efficient tours, and yet, tour construction is handled autonomously by each agent, making tour efficiency depend on the agent's routing skills. Against this background, we introduce a novel behavior-aware customer-to-agent assignment approach, which uses algorithmic nudging to support agent's in the autonomous construction of distance-minimizing tours. In an experimental study with human decision makers, we provide evidence that our approach leads to a significant and economically meaningful reduction in total tour length. Accordingly, gig-economy companies can benefit from our work as we offer an alternative to traditional customer-to-agent assignments, enabling agents to construct efficient yet self-determined tours.

■ FA-21

Friday, 8:30-10:00 - ESA W(est) 122

Sustainability and Business Analytics

Stream: Analytics, Forecasting and A.I.
Invited session
Chair: *Sandra Zajac*
Chair: *Pirmin Fontaine*

1 - Measuring Environmental Awareness: An Analysis Using Google Search Data
Matthias Horn, Amal Dabbous, Alexandre Croutzet

Environmental awareness is usually measured using surveys. This paper aims to offer an alternative measure: an Environmental Awareness Index (EAI) constructed using Google search data provided by Google Trends. To test the validity of the proposed EAI, this study empirically assesses the impact of the computed index on individuals' environmentally friendly behavior using the Eurobarometer data. Results show that the EAI is positively related to environmental-friendly behavior with a statistical significance at the one percent level. This finding stays robust in pooled OLS as well as in panel regression analysis when GDP, mean years of schooling, and population are included as control variables and when time-fixed effects are introduced. Further, the results confirm that environmental awareness is not stable over time and underline the importance of having a timely measure of environmental awareness at hand.

2 - Sustainable development of Polish and Lithuanian regions and education of the society
Dorota Górecka

In 2015, the Sustainable Development Goals (SDGs) replaced the Millennium Development Goals as reference goals for international development for 2015-2030. Among them, quality education was singled out as a separate goal no. 4 (SDG 4). So far, a number of links between education and training and other areas of sustainable development have been documented, including in United Nations (UN) publications. Many of these links are also noticed by decision makers. UN global reports show connections between education and all the Sustainable Development Goals except SDG 14 on life below water. For most of the goals, causal relationships have been identified in both directions: from education to other target areas and vice versa. The links between education and decent work and economic growth (SDG 8) as well as gender equality (SDG 5) are most emphasized. In turn, relationships with affordable and clean energy (SDG 7), clean water and sanitation (SDG 6), sustainable cities and communities (SDG 11), responsible consumption and production (SDG 12) as well as climate action (SDG 13) receive much less attention [Vladimirova, Le Blanc, 2016]. Taking into account the relations between Poland and Lithuania dating back to the 13th century, the aim of the presentation is to assess the level of implementation of the concept of sustainable development in two Lithuanian and seventeen Polish regions at the NUTS 2 level, as well as verification of the relationship between education and other objectives of harmonious development in this area. The study uses the TOPSIS method [Hwang, Yoon, 1981; Lai, Liu, Hwang, 1994] and a modified BIPOLAR method [Górecka, 2009; Górecka, Muszyńska, 2011]. The analysis is based on data provided by Eurostat.

3 - A Machine-Learning Approach to Optimizing Re-Usable Packaging for E-commerce Returns
Lucas Clement, Stefan Spinler

The inability to physically inspect products before purchase often leads to high return rates in e-commerce, which in turn result in significant costs for retailers and ecological concerns due to additional transportation, packaging, and disposal of unused items. To address these issues, we propose a novel approach by leveraging machine learning to predict the likelihood of returns and optimize the use of re-usable packaging. We investigate the application of a reusable packaging system designed for orders with a high probability of being returned at least partially. This approach aims to increase re-usability, limit packaging disposal, and reduce costs associated with re-usable packaging for orders where returns are unlikely. We develop a machine-learning-based return prediction algorithm that utilizes customer and order-level information to assess the likelihood of a return on a shipment-level basis. In addition, we explore which input features are most influential in predicting return likelihood using Shapley values. We apply the method to data from a large e-commerce retailer, and show that the prediction algorithm significantly improves accuracy. We find that various machine learning algorithms perform similarly, with neural networks showing a slight advantage. Furthermore, we demonstrate that order size, similarity of items, and specific product categories are the most important factors in predicting return likelihood. Our study contributes to the operations research field by offering a data-driven solution to optimize re-usable packaging for e-commerce returns. The proposed approach not only reduces costs but also helps mitigate the environmental impact of e-commerce returns, aligning with the increasing focus on sustainability in the industry.

4 - Optimal Software Scheduling Decision Using Multi-Attribute Utility Theory
Avinash K Shrivastava

Various authors have developed software reliability models and related cost models to determine the optimal release time in the existing literature on software reliability. Literature suggests that it is better to segregate the software lifecycle's release and testing termination time. But all the existing literature in this direction assumes that the cost of providing an update post-software release is negligible. But it looks impractical in a real-life scenario and needs to be re-considered while developing the cost model. This cost of providing patches during the post-release testing phase impacts the total software development cost and hence the software scheduling policy. I have developed a multi-attribute utility function with the help of a software cost and reliability model and optimized it to obtain the optimal release, patching and testing termination. A numerical illustration of the proposed model is done on a real-life data set.

■ FA-22

Friday, 8:30-10:00 - ESA W(est) 220

Scheduling and Transportation Problems

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *Caroline Spieckermann*

1 - A dynamic multi-commodity flow time-space network generation approach to exactly solve multiple duty type transit crew scheduling for large real world problems

Lucas Mertens, Natalia Kliewer

The transit crew scheduling problem (CSP) involves the cost-minimal assignment of duties to vehicle trips while satisfying constraints such as work regulations and operational guidelines. The CSP has been extensively studied in transportation research, and state-of-the-art approaches are able to solve CSP for large real-world problems efficiently. However, recent research focuses on the benefits of integrated solving multiple public transport planning steps, and most traditional CSP approaches are not applicable in an integrated optimization. We propose a dynamic multi-commodity flow time-space network generation approach that is able to solve large real-world CSP for multiple duty types and can be applied in a threefold integration of timetabling, vehicle, and crew scheduling. By dynamically adding and cutting layers in the time-space network, duties are added iteratively, and computing the cost-minimal duty schedule is guaranteed in the long run. Compared to most state-of-the-art approaches, the proposed formulation can start well from an initial solution and is capable of evaluating the benefits of adding new duty types to existing duty schedules. Even though the new approach does not outperform every traditional CSP formulation regarding runtime for the single planning step, close to optimal results are already computed in a significantly shorter runtime. However, with increasing runtime, computing the optimal solution is guaranteed. We further give an outlook on how the approach can be utilized in a threefold integrated optimization of timetabling, vehicle, and crew scheduling and reduce the overall costs or further increase the service quality as a result.

2 - A Decision Support System for Nurse Rostering using Mixed Integer Programming

Samuel Kolb, Reinhard Bürgy, Harold Tiemessen, Simon Haug

Shift work makes it difficult for healthcare workers to balance work and personal life. Negative effects of shift work can be reduced by giving employees more and better opportunities to shape their working schedule. Currently, there is a lack of tools for automated schedulers that take into account the needs and requirements of all stakeholders. Intelligent and participative shift scheduling via a Decision Support System (DSS) considers the needs of employees and relieves the burden on planners by simplifying the scheduling process. The DSS is highly participative since nurses can help shape their schedules by entering their needs and preferences in the system. In collaboration with three healthcare institutions, we develop a DSS that contains mathematical programming models and powerful solvers and supports varying nursing demand per skill during the week, working time regulations, employees needs and preferences, et cetera. In our mathematical programming models, we use employee-specific workday patterns as decision variables. This allows for considering complex working time regulations and formulating and modelling employee preferences. These workday patterns are generated in a preprocessing step by using simple construction heuristics that consider working time regulations and employee preferences. Our DSS is tested in three different healthcare settings in Switzerland. In an iterative process, the shift planner and the software find good schedules in a short time. The participative approach led to great acceptance among the healthcare institutions involved in the project and the results of the tests are very promising.

3 - A Column Generation Driven Heuristic for Order-Scheduling and Rack-Sequencing in Robotic Mobile Fulfillment Systems

Jan-Erik Justkowiak, Erwin Pesch

The order picking process in robotic mobile fulfillment systems, a warehousing technology following the parts-to-picker concept, involves two interlinked decisions: How to schedule the processing of orders and how to sequence the racks that are lifted and transported by automated guided vehicles (robots) to the picking-station to supply the requested items (so called rack-visits)? It is shown in literature that minimizing the number of rack-visits is well suited to operate a picking-station efficiently, that is, reducing robot utilization as well as the makespan of customer-order processing. We present a heuristic solution approach for the order-scheduling and rack-sequencing problem at a single picking-station using column generation to partition the set of orders into batches, while minimizing the number of rack-assignments to batches, which in turn minimizes the rack-visits. The generated batches possess a property that allows to derive an order-processing schedule and rack-sequence straightforwardly. Then, we refine the heuristic solution by rearranging the processing of batches and their assigned racks. A comprehensive and comparative computational study demonstrates superior performance of our approach on the vast majority of instances compared to several heuristics, both in terms of solution quality and runtime. It is also shown that the heuristic provides good results on small-case data when embedded into a framework to solve the problem at multiple picking-stations.

4 - A GNN-based Edge Predictor for the Fixed-Charge Transportation Problem

Caroline Spieckermann, Stefan Minner, Maximilian Schiffer

The Fixed-Charge Transportation Problem (FCTP) is a well-known combinatorial optimization problem whose NP-hardness requires the application of efficient algorithms to obtain good solutions in a reasonable amount of time. We present a machine learning-based heuristic for the FCTP that aims at reducing the problem complexity by predicting a relevant subset of edges. The reduced problem can be solved efficiently with an exact or heuristic FCTP solver. We base the edge predictor on a bipartite graph neural network (GNN) that is both parameter-efficient and problem size-agnostic. We evaluate the performance on various FCTP benchmark data sets to analyze the impact of different structural properties, such as the supply-demand-ratio and the ratio of total flow and fixed costs, on the problem complexity and edge predictability. The GNN shows good prediction and generalization capabilities that translate into high quality solutions across all data sets (optimality gaps below 1%) while runtimes are reduced by 60-90%. When runtimes are limited, the problem reduction leads to better solutions in comparison to solving the full problem by providing an effective reduction of the search space. Similarly, the solution quality of two established metaheuristic solvers (Tabu Search, Evolutionary Algorithm) can be systematically improved through the GNN-based pre-filtering of edges. Comparing different structural properties, the supply-demand-ratio has the strongest impact on edge predictability and solution qualities, with higher prediction accuracies and lower optimality gaps when there is a surplus of supply.

■ FA-24

Friday, 8:30-10:00 - ESA O(st) 120

(Resource Constrained) Project Planning

Stream: Project Management and Scheduling
Invited session
Chair: *Max Reinke*

1 - An adaptive large neighbourhood search procedure for solving an integrated project and personnel scheduling problem

Brede Sørøy, Benjamin Buan, Anders N. Gullhav

We propose an adaptive large neighbourhood search (ALNS) procedure to solve an integrated project and personnel scheduling problem. Our problem involves scheduling activities in one or more projects, allocating personnel and equipment, and minimising total costs while completing all activities in a given time horizon. The activities are preemptive and multi-modal. This means that activities can be interrupted after they have started and that there are many ways to complete the activities, varying in duration and resource demand. The required resources are personnel from a heterogeneous workforce and different types of equipment that are transported between activities and projects.

We know from theory that the integrated solution always is equally good or better than scheduling projects and personnel separately. However, the integrated problem is hard to solve when the number of projects increases. Our proposed ALNS includes several destroy and repair operators and is tested on 1,500 instances with a computation time of five minutes per instance. We compare our results with the solutions obtained from an exact method for the integrated problem having a maximum computation time of three hours per instance.

After five minutes of execution, our ALNS finds solutions that are almost as good as those from the exact method after three hours. Warm starting the exact method with the ALNS solutions improves the exact method's performance further. Our proposed procedure has practical implications for companies from the construction industry that need to schedule projects and allocate resources effectively. It reduces overall costs and improves efficiency, highlighting the potential of heuristic methods to solve integrated project and personnel scheduling problems efficiently.

2 - An advanced generation scheme for the resource-constrained project scheduling problem with generalized precedence constraints and partially renewable resources

Mareike Karnebogen, Jürgen Zimmermann

Partially renewable resources have a total capacity assigned to a certain subset of periods of the plan-ning horizon. As part of project scheduling, the resource consumption of the activities executed in the limited periods of a partially renewable resource must not exceed its capacity in total. This allows more specific resource restrictions, such as flexible working hours.

In the talk, we consider the resource-constrained project scheduling problem with generalized prece-dence constraints and partially renewable resources (RCPSP/max,π). For this, it is known that already the determination of a feasible solution is NP-hard in the strong sense and - despite the regular objec-tive function - neither the sets of active nor quasi-active schedules always contain an optimal solution for each problem instance. We present a multi-start generation scheme, which is able to find feasible solution for nearly all tested instances. To further improve the performance of the heuristic, it is ex-tended by machine learning techniques, both to predict the minimum project duration and to learn from previous iterations or runs in the further course of the generation scheme.

3 - An adapted fix-and-optimize heuristic for the resource renting problem with general temporal constraints

Max Reinke, Jürgen Zimmermann

Often in projects, resources are required which are not at hand but rather have to be rented. This is taken into account by the resource renting problem (RRP/max) introduced in Nübel (2001), an extension of the well-known resource availability problem (RAP/max). In addition to the time-independent procurement cost, time-dependent renting costs are considered, which only arise when a resource is rented and therefore available to the project. If procurement costs are significantly higher than renting costs for a resource unit, it may be beneficial to keep renting a resource, even when it is idle and not in use, rather than paying the procurement costs again later. A Solution to the RRP/max consists of a time-feasible Schedule and a renting policy that specifies the time and amount for the procurement and release of resources. The RRP/max can be solved using a MILP model as proposed by Reinke and Zimmermann (2021). In our work, we developed a MILP-based fix-and-optimize heuristic to solve the RRP/max. The heuristic exploits the structural properties of the problem, like the fact an optimal solution can be found among the quasistable schedules, to create smaller subproblems that are easier to handle for a solver and are therefore faster to solve. For this, a subset of the activities is chosen to remove from the schedule and reoptimize their start times, by rescheduling them locally optimal. Within a performance analysis, we show the effect of different strategies to create subproblems and compare the results regarding the solution quality and time to those obtained by the MILP model.

■ FA-25

Friday, 8:30-10:00 - ESA O(st) 222

Last-Mile Delivery

Stream: Pricing and Revenue Management
Invited session
Chair: *Matthias Soppert*

1 - On the impact of overlapping time windows in attended home delivery

Katrin Waßmuth, Niels Agatz, Moritz Fleischmann

The online grocery business continues to be rapidly growing. We are seeing highly dynamic developments with new business models entering the market and established players rethinking their delivery service offering. At the same time, research into demand management for such attended home delivery services is maturing. Contributions focus mainly on real-time operational and on tactical demand management. Those approaches commonly assume a given template of delivery time windows which serves as the basis for the retailer's offering and pricing decisions. What is much less well understood is the design of the time window template itself on the strategic level. In this paper, we contribute to filling this gap by investigating one of the dimensions of common time window templates, namely time window overlaps. Based on our analysis, we derive conditions under which it is, or it is not beneficial to offer such options. While an additional overlapping time window increases the demand volume it may result in an unfavorable distribution of demand, thereby harming delivery efficiency. We investigate this trade-off. To this end, we develop a stylized model that captures demand effects and evaluates expected fulfillment costs, using continuous approximation. We then use nonlinear optimization to identify how to best use the flexibility resulting from overlapping delivery time windows.

2 - Subscription-based models for maximizing profitability in e-grocery retailing

Charlotte Köhler, David Winkelmann

E-grocery retailing is characterised by narrow profit margins and high customer expectations. Retailers aim to provide their customers with an excellent level of service, such as a wide product selection and short delivery times. However, as overall customer demand is unknown, this leads to high costs in inventory holding for products as well as inefficient and costly delivery routes. Thus, to reduce operational costs and increase profits, retailers aim at reducing demand uncertainty while maximising the level of customer retention. In this presentation, we propose a subscription-based model for e-grocery retailing: Customers commit to a selection of products to be delivered at regular intervals and companies reward this commitment by offering benefits such as discounts for the selected products. Higher benefits are likely to attract more customers to subscribe to a specific retailer. However, the retailer must calculate expected savings for each subscriber to determine the benefits they can offer. We will show that implementing a subscription-based model can help retailers to decrease demand uncertainty, improve operational planning, and enhance customer locality in the long run.

3 - Hierarchical demand management decomposition for online vehicle routing problems

Vienna Klein, Robert Klein, Claudius Steinhardt

The evolution of e-commerce has led to the emergence of new business models in last-mile delivery, especially regarding applications that require online tour planning. In same-day delivery (SDD), e.g., customers log in to an e-commerce platform, place an order, and expect its delivery within a few hours. This comes along with very high customer expectations regarding delivery speed. Consequently, in order to still operate profitably, managing last-mile delivery has evolved from optimizing fulfillment operations alone to, additionally, steering demand, i.e., integrated demand management and vehicle routing problems (i-DMVRPs) have emerged. The accompanying high practical relevance of i-DMVRPs with an online tour-planning component, has prompted the progression of the research of stochastic dynamic vehicle routing problems toward integrating ideas from traditional revenue management literature. However, to the best of our knowledge, there exists no research that structurally analyses the application of choice-based linear programming (LP) models to solve online i-DMVRPs. Since

choice-based LP models have proved to be very valuable in traditional demand management control mechanisms, we aim at closing this research gap: We introduce a concept of how to integrate choice-based demand management into an LP approach for online vehicle routing, in which both the vehicle routing as well as the demand control are optimized simultaneously. Thereby, we focus on an SDD problem in which an e-retail provider offers different delivery options for ordered goods to sequentially incoming customers, who then choose stochastically, according to their choice preferences. However, it is straightforward to transfer the concept to other i-DVMRPs.

4 - Compensation Optimization for Occasional Drivers in Crowd-Sourced Delivery
Matthias Soppert, Kai Winheller, Rouven Schur

With the growth of e-commerce, last-mile delivery has become increasingly important. Since the costs associated with this service are high and decisively impact profitability, firms have begun exploring crowd-sourced delivery approaches, such as engaging occasional drivers (ODs) who use their personal vehicles for delivery. First research on this topic typically takes various simplifying assumptions, in particular regarding the firm's and the ODs' decision making, as well as regarding the availability of information. For example, the compensation amount is pre-defined, and the firm has perfect knowledge about ODs' availability. Further, ODs cannot decide between delivery task alternatives. These simplifications allow to formulate optimization approaches as deterministic assignment problems in which ODs are matched to delivery tasks. In our work, we consider the engagement of ODs as well as the interaction between firms and ODs more realistically. Specifically, we assume uncertain OD arrivals as well as an OD choice behavior that considers potential detours, the compensation amount, and potential delivery task alternatives. Additionally, we allow the firm to decide on the compensation scheme by formulating and solving a corresponding compensation optimization problem.

Friday, 10:30-11:30

■ FB-02

Friday, 10:30-11:30 - ESA B

Semi-plenary talk Manlove

Stream: PC Stream
Semi-plenary session
Chair: *Marc Pfetsch*

1 - Models and Algorithms for Kidney Exchange
David Manlove

A patient who requires a kidney transplant, and who has a willing but incompatible donor, may be able to 'swap' his or her donor with that of another patient, who is in a similar situation, in a cyclic fashion. Non-directed (altruistic) donors can also trigger 'chains' of transplants involving multiple recipients together with their willing but incompatible donors. Kidney exchange programmes (KEPs) organise the systemic detection of optimal sets of cycles and chains based on their pools of donors and recipients. There are many examples of KEPs around the world, including the UK Living Kidney Sharing Scheme (UKLKSS). In this talk I will describe integer programming models and algorithms that can be used to solve the underlying optimisation problem involved in a KEP. In particular I will present a new hybrid algorithm for hierarchical optimisation for use with the UKLKSS that involves cycle / chain deactivation via reduced cost variable fixing, objective diving and dominated chain detection. This is joint work with Maxence Delorme, Sergio García, Jacek Gondzio, Joerg Kalcsics and William Pettersson.

■ FB-06

Friday, 10:30-11:30 - ESA C

Semi-plenary talk Müller

Stream: PC Stream
Semi-plenary session
Chair: *Asvin Goel*

1 - Locational choices and decisions: choice-based facility location planning
Sven Müller

Many organizations face the challenging problem of locating facilities. For instance, retailers or restaurant chains aim to find locations for their branches such that the expected sales, revenues, or profits are maximized. Health care and educational authorities may desire to locate facilities in such a way that patronage or participation is maximized. All these objectives have in common that they are functions of the expected demand for the products and/or services offered at the located facilities. The demand for a particular facility location depends on all located facilities. As such, demand is treated as a variable rather than a parameter in the optimization model. Here, demand is predicted using a discrete-choice model. In fact, discrete-choice models predict the probability that a customer (segment) chooses to visit a given location. The various challenges (non-linearities, non-convexities) that come a long with the incorporation of discrete choice models in optimization models for facility location planning are discussed. On top of that some tailored solution methods and applications are presented.

Friday, 12:00-13:30

■ FC-01

Friday, 12:00-13:30 - ESA A

Plenary Talk Topaloglu & Closing Event

Stream: PC Stream
Plenary session
Chair: *Alexander Martin [GOR President]*

1 - Incorporating Discrete Choice Models into Operations Management Models
Huseyin Topaloglu

Over the last couple of decades, there has been enormous progress in using discrete choice models to understand how customers choose and substitute among products and incorporating this understanding into operational models to decide which assortment of products to offer to customers or what prices to charge. We owe some of this progress to increase in the computational power so that we can build and solve more detailed operational models, but perhaps, most of this progress is due to the fact that online sales channels started providing fine-grained data on how customers browse the products. In this talk, we will go over fundamental discrete choice models that have been used in building operational assortment optimization and pricing models, overview the main algorithmic approaches that have been developed to solve the operational models, and identify research prospects. The focus will be on both static models that make one-shot assortment optimization or pricing decisions, as well as dynamic models that explicitly capture the evolution of demand and inventories over time.

Analytics, Forecasting and A.I.

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Choice Based Analytics

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Track(s): 10

Continuous and Global Optimization

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Decision Analysis and Support

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Discrete and Combinatorial Optimization

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Financial Management and Investments

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Game Theory and Behavioral Management Science

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Health Care Management

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Heuristics, Metaheuristics and Matheuristics

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Mobility and Traffic

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Track(s): 13 14

OR in Developing Countries

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OR in Engineering

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Track(s): 4 23 25

PC Stream

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Track(s): 1 2 6 7 8 10 12 22

Pricing and Revenue Management

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Project Management and Scheduling

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Simulation, Reinforcement Learning and Quantum Computing

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Software for OR

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Supply Chain Management

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