Wednesday, 8:30-10:00

■ WA-01

Wednesday, 8:30-10:00 - 30.95 Audimax A & B

Opening Ceremony & EURO Plenary talk Speranza

Stream: PC Stream
Plenary session
Chair: *Stefan Nickel*

1 - Optimization in transportation and logistics: yesterday, today, tomorrow
M. Grazia Speranza

Technological changes have been dramatic in the last decades and are changing the way people move and goods are transported. The Internet of Things (IoT) makes objects and places capable of receiving, storing and transmitting information. On the other hand, sustainability is a challenge for institutions, companies, researchers Coordination opportunities are enormous. A systemic approach to problems and advanced analytical methods are even more vital than in the past. In this talk, starting from the research carried out in the past, the main trends in the use of optimization models for problems in transportation and logistics will be presented and some research directions will be discussed.

Wednesday, 10:30-12:00

■ WB-04

Wednesday, 10:30-12:00 - 10.11 Hertz-Hörsaal

GOR PhD Thesis Awards 2022

Stream: PC Stream
Award Competition session
Chair: *Peter Letmathe*

1 - Resident scheduling in teaching hospitals
Sebastian Kraul

After graduation, physicians receive further training in a medical domain like anesthesiology. There are 57 medical specialties in Germany in total. The high cost pressures of hospitals and the changing view of the medical profession regarding the work-life balance have led to recruitment problems and low employee satisfaction in many places. A promising approach to counter this problem is objective and structured training planning. This research project mainly deals with the strategic and tactical-operative training scheduling of medical residents. In addition to relieving the medical staff currently responsible for the planning process, this research project increases the predictability of structured training. A structured training allows hospitals to increase the quality of their training and, consequently, their attractiveness to other hospitals. In addition, supervisors from different departments can better assess residents' knowledge and thus keep the level of service, which is particularly important in hospitals, permanently high even when changing residents. From the residents' point of view, a well-structured training schedule enables a high degree of information. Therefore, residents are no longer surprised by a short-term change of department and have a direct insight into their training progress. A real-world case study evaluates the mathematical formulations and the solution approaches.

2 - Faster algorithms for Steiner tree and related problems: From theory to practice
Daniel Rehfeldt

The Steiner tree problem in graphs (SPG) is one of the most studied problems in combinatorial optimization. The SPG has seen impressive theoretical advancements in the last decade, but the state of the art in (practical) exact SPG solving has remained largely unchallenged for almost 20 years.

This thesis seeks to advance exact SPG solving once again. Since many practical applications are modeled not as pure SPGs, but rather as closely related problems, we also aim to combine SPG advancements with improvements in the exact solution of such related problems. Initially, we provide various new theoretical results for SPG and well-known relatives, such as the maximum-weight connected subgraph problem. These results include the strength of linear programming relaxations, polyhedral descriptions, and complexity results. Next, we introduce many new algorithmic components such as reduction techniques, cutting planes, graph transformations, and heuristics—both for SPG and related problems. Many of these methods and techniques are provably stronger than previous results from the literature.

The individual components are combined in an exact branch-and-cut algorithm. As a result, we obtain an exact solver for SPG and 14 related problems. The new solver is on each of the 15 problem classes faster than all other solvers from the literature (including problem-specific ones), often by orders of magnitude. In particular, the new solver outperforms the long-reigning, but non-public, state-of-the-art SPG solver by Polzin and Vahdati Daneshmand. Even geometric Steiner tree problems can be solved much faster than previously possible when the new solver is combined with the full Steiner tree generation provided by the software GeoSteiner. Finally, with our new solver, many benchmark instances from the literature for several problem classes can be solved for the first time to optimality—some containing millions of edges. These problem classes include the SPG, the prize-collecting Steiner tree problem, the maximum-weight connected subgraph problem, and the Euclidean Steiner tree problem.

The software developed for this thesis, named SCIP-Jack, has been made freely available with source code for academic use (https://scipjack.zib.de/). Already a previous and significantly slower version of SCIP-Jack obtained top rankings in all tracks of the PACE

Challenge 2018. Finally, SCIP-Jack is heavily used in several industrial projects, for example, at Open Grid Europe, one of Europe's largest transmission systems operators.

3 - Prescriptive Analytics for Data-driven Capacity Management
Pascal Notz

Machine learning (ML) constitutes a new field of research in Operations Research (OR): prescriptive analytics approaches integrate ML prediction and OR optimization to derive future decisions for OR planning problems from historical observations of demand and a set of features (co-variates). The author's dissertation develops new prescriptive approaches to complex capacity planning problems and uses these to solve realistic planning problems along three independent articles. The first article develops two prescriptive analytics approaches, weighted sample average approximation (wSAA) and kernelized empirical risk minimization (kERM), to solve a complex two-stage capacity planning problem: a logistics service provider sorts daily incoming mail items on three service lines that must be staffed on a weekly basis. The second article uses wSAA and kERM to solve the (queuing-type) staffing problem of an aviation maintenance provider that receives customer requests at uncertain arrival times and plans staff capacity for two shifts, building a foundation for solving queuing-type problems using prescriptive analytics. The third article proposes a novel prescriptive analytics approach that allows decision-makers to derive explanations for prescribed decisions: Subgradient Tree Boosting. The results presented in these three articles demonstrate that using prescriptive analytics to solve capacity planning problems can lead to significantly better decisions compared to traditional approaches that neglect feature data or rely on a parametric distribution estimation.

4 - Algorithms for Mixed-Integer Bilevel Problems with Convex Followers
Thomas Kleinert

Hierarchical decision making processes naturally appear in an enormous amount of applications from areas including energy markets, revenue management, machine learning, critical infrastructure defense and many more. Such processes are formalized by bilevel optimization problems, i.e, optimization problems for which a subset of variables is constrained to be an optimal solution of another optimization problem. Since bilevel optimization problems are inherently nonconvex, they are notoriously hard to solve both in theory and practice—which makes bilevel optimization an exciting area of research.

In the presented dissertation, we introduce and evaluate several algorithms for mixed-integer bilevel problems with convex lower levels. First, we review branch-and-bound methods for linear bilevel problems, critically discuss their practical use, and propose valid inequalities to extend the methods to branch-and-cut approaches. Further, we demonstrate that it is no longer necessary to use the well-known but error-prone big-M reformulation to solve linear bilevel problems. Next, we present a heuristic that is based on a penalty alternating direction method and that is applicable to a broad class of bilevel problems. We show that the heuristic computes (close-to-)optimal feasible points in very short computation time and that it outperforms a state-of-the-art local method. Finally, we introduce an MINLP-inspired global approach for mixed-integer quadratic bilevel problems and demonstrate that it outperforms known benchmark algorithms.

■ WB-05

Wednesday, 10:30-12:00 - 11.10 Engelbert-Arnold-Hörsaal (EAS)

Sustainability in Supply Chains

Stream: Supply Chain Management
Invited session
Chair: *Müge Çakan*

1 - Designing renewable fuel supply production networks for the transition towards a defossilized transport sector
Mohammad Zardoshti Zadeh Yadi, *Grit Walther*

Recent roadmaps and regulations are forcing the transportation sector to a transition from fossil fuels to renewable energy sources. Herein, renewable fuels will play a major role for mobility modes like aviation or shipping that cannot be electrified. However, there are several obstacles, including immature and small-scale fuel production pathways, strong competition for the resource utilization such as renewable electricity and biomass, and uncertainties in renewable fuel supply networks, such as seasonal supply of wind and solar power. So far, models for the design of renewable fuel production networks do not sufficiently consider the required long-term planning horizon, the multiple renewable fuel production pathways, and seasonal resource availability in an integrated way. Hence, we develop an integrated model for the design of renewable fuel production networks considering the long-term planning horizon, promising production pathways, fuel transportation and storage as well as availability of annual seasonal resources. Our modeling approach considers various strategic (e.g., multi-period decisions on locations for fuel production facilities, storage capacity, and transportation infrastructure) as well as tactical decisions (e.g., seasonal production, transportation, and storage decisions along with annual seasonal resource utilization). We aim to determine a network configuration that satisfies renewable fuel demand, thereby determining the cost-effective design of the supply network and its deployment over a long-term horizon and efficient use of limited resources. To illustrate the implications of our modeling approach, we present results for a European-wide case study analyzing efficient renewable fuel infrastructure until 2060.

2 - Allocation of recycling credits to final products in plastics production
Müge Çakan, *Moritz Fleischmann*, *Danja R. Sonntag*

In recent years, chemical recycling has emerged as a complementary technology that enables treatment of plastic waste that cannot be mechanically recycled. A specific feature of the chemical treatment is that it produces recycled feedstock that is chemically indistinguishable from virgin feedstock. This property gives rise to a new planning problem for plastic manufacturers, namely, how to allocate the recycled material content - and corresponding certificates - to different final products produced from a mix of recycled and virgin feedstock. Current legislation surrounding this decision is quite lenient, leaving chemical manufacturers room to choose a suitable allocation. NGOs criticize the current practice as prone to greenwashing and ask for more restrictive allocation rules. In this project, we contribute to the ongoing debate by systematically analyzing the implications of different allocation rules using a game-theoretic approach. We investigate the manufacturer's choices and the implied economic and environmental performance for different allocation rules. By comparing the results, we are able to highlight the consequences of different policies referred to in the current debate.

3 - Carbon foot print optimization in the European cement industry
Ingmar Steinzen, *Dominik Hollmann*, *Stefan Bunte*, *Jens Peter Kempkes*

For the cement industry, the implementation of the EU carbon dioxide regulations is essential. In order to achieve optimal planning in production networks with more than 100 locations, complicated product recipes and deep bill of materials, an optimization software has been introduced. This presentation shows aspects of the mathematical model and the software product.

■ WB-06

Wednesday, 10:30-12:00 - 10.91 Redtenbacher-Hörsaal

Decision Support for Personnel Management

Stream: Decision Analysis and Support
Invited session
Chair: *Sandy Heydrich*

1 - A DEA-based approach for a thorough analysis of the efficiency of a national public university system. Application to Spanish public universities.
Sebastián Lozano, *Ignacio Contreras*, *Ignacio Eguia*

Data Envelopment Analysis (DEA) is proposed for carrying out a thorough analysis of a national public university system with the aim of maximizing its efficiency. It involves three phases. First of all, the current technical and size efficiency of the different universities is assessed and those that might be split are identified. Then, the gains from potential mergers of universities are individually evaluated. In order to

limit the number of merger combinations to explore, geographical or administrative criteria can be used. After the re-structuring carried out in these two phases, in the third phase the reallocation of transferable resources between the universities is studied. The efficiency gains provided by each of these phases can be quantified. Moreover, their cumulative effect can represent a significant overall efficiency improvement. The proposed approach has been applied to the Spanish national public university system.

2 - Forecasting personnel requirements at a pharmaceutical production site during clinical trials
Sandy Heydrich, Heiner Ackermann, Stella Dohn, Elisabeth Finhold

We study a capacity planning problem arising in the field of research and production for personalized cancer therapy. In this therapy, patients become part of the pharmaceutical supply chain as they provide blood and tissue samples that are used as inputs for the manufacturing of their personalized drug. One challenge in the production process is the short shelf-life of some of these samples. To guarantee the timely processing of the samples, it is important to always have sufficient laboratory staff available. However, the stochastic nature of the recruitment and the patients' sample arrivals make it challenging for the manufacturing site to perform strategic personnel resource planning . Therefore, we use parameters defined in the study design as well as historical data from previous trials to forecast sample arrivals at the production site. The amount of sample arrivals is then used to derive the personnel requirements and to support staff planning. We developed a Monte Carlo simulation tool that generates, for a given set of studies, newly recruited fictitious patients, and their sample arrivals. By means of this tool, we can predict sample arrivals of to-be-recruited patients for every day in the simulation's time horizon and thereby forecast the capacity requirements at the production site. We then use the simulation results to compute the required amount of laboratory staff by means of bin packing algorithms and configuration LP. The outcome of our tool is to be used as decision support during strategic personnel resource planning at the production site.

3 - The sales force deployment problem for teams of sales representatives within sales territories
Tobias Vlcek

We address the sales force deployment problem and its four subproblems for teams of sales representatives within sales territories. We contribute by showing that the problem can be reduced to the uncapacitated facility location problem under convex profit contribution functions with a unique maximum. In our numerical study, we show that instance sizes considered difficult for the sales force deployment problem of individual representatives can be solved optimally in minutes for teams of representatives. In our largest instance, with 2020 potential locations and sales coverage units, it took on average 140.73 seconds.

4 - A Delphi Method Reinforced Decision Model for Evaluating Architectural Design Projects
Nil Akdede, Ozay Ozaydin

Architecture is the art and science of designing and constructing buildings and other physical structures. Architecture plays a significant role in our lives - it shapes the way we live, work and play. Architecture also reflects our society and our values. As such, it is important that architectural education prepares students for the challenges of designing and constructing buildings that are safe, functional and aesthetically pleasing. The Delphi Method is a well-established tool for gathering and processing expert opinion. It has been used extensively in a wide range of fields, including architecture. The purpose of this study was to develop a Delphi-based decision model for evaluating architectural design projects in architectural education. The study was conducted in two rounds, with 4 experts participating in each round. The results of the study showed that the Delphi Method can be a valuable tool for creating a more robust input to be used in Analytical Network Process to evaluate architectural design projects in architectural education.

■ WB-07

Wednesday, 10:30-12:00 - 10.91 Grashof-Hörsaal

Multiobjective Integer and Combinatorial Optimization

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

1 - Combinatorial Optimization with Ordinal Costs
Kathrin Klamroth, Michael Stiglmayr, Julia Sudhoff

We analyze combinatorial optimization problems with ordinal, i.e., non-additive, objective functions that assign categories (like good, medium and bad) rather than real-valued cost coefficients to the elements of feasible solutions. For example, when searching for safe bike routes we may want to use many streets that have a bike lane (i.e., safe streets) and few congested streets with lots of cars and trucks (i.e., unsafe streets). However, it is generally unclear whether one safe street can make up for one unsafe street, or maybe even for two or more unsafe streets, if at all. In other words, the ordinal cost coefficients are non-additive in general, which necessitates the development of tailored ordering relations and optimality concepts.

In this talk, we first review different optimality concepts for ordinal optimization problems suggested in the recent literature and discuss their similarities and differences. Our main result is a bijective linear transformation that transforms ordinal optimization problems to associated standard multi-objective optimization problems with binary cost coefficients. Since this transformation preserves all properties of the underlying problem, problem-specific solution methods remain applicable. A prominent example is dynamic programming and Bellman's principle of optimality, that can be applied, e.g., to ordinal shortest path and ordinal knapsack problems. We extend our results to multi-objective optimization problems that combine ordinal and real-valued objective functions.

2 - Optimization-pessimization method for robust multiobjective optimization
Fabian Chlumsky-Harttmann, Marie Schmidt, Anita Schöbel

In our work we consider multi-objective optimization problems with uncertainty. These are problems where the objective function value depends not only on the chosen solution from the feasible set but also on the realization of a scenario from a predefined uncertainty set. Our aim is then to determine solutions that are not only efficient for the multiobjective-optimization problem but also robust against all possible outcomes. In recent years, robustness concepts from single-objective robust optimization have been generalized. However, solution methods are scarce. We employ a generalization of minmax robustness, called minmax robust efficiency by Kuroiwa and Lee (2012) and develop algorithmic methods to find such solution. For this purpose, we consider an iterative procedure well-known in (single-objective) robust optimization called, optimization-pessimization method. The approach is based on the idea of performing an optimization step and a pessimization step alternately. In each optimization step, a smaller problem with only a reduced uncertainty set is solved and a robust solution is determined. In the subsequent pessimization step, the worst-case scenario for the previously found robust solution is computed and then added to the uncertainty set. Ultimately, this results in a cutting plane approach. In a multiobjective setting, both the optimization problem and the pessimization problem involve multiple objectives. We show how the optimization-pessimization method can be generalized to such problems and under what conditions correctness and finiteness of the approach can be guaranteed.

3 - Weighted Set Decompositions of Weighted Norm-Based Scalarizations for Multiobjective Discrete Optimization Problems
Kathrin Prinz, Stephan Helfrich, Stefan Ruzika

Scalarization is a frequently applied technique that transforms a multiobjective programming problem into a scalar-valued optimization problem to obtain an efficient solution or nondominated image. Many scalarizations specify weights and minimize the weighted distance to a fixed reference point - the weighted norm-based scalarizations.

For the weighted sum and weighted Tchebycheff scalarization, both being norm-based scalarizations, the set of eligible weights has been studied with a successful application of a weight set decomposition approach: the set of eligible weights is divided into subsets such that

all weights in a subset yield the same image of an optimal solution under the objective function. Doing so, the structure of the set of eligible weights is linked to the structure of set of images and provides additional information, such as robustness and adjacency of images. Hence, the understanding of the structure of the weight set decomposition is particularly useful as an additional support for a decision maker when selecting their most preferable solution or image. We apply the weight set decomposition approach to different norm-based scalarizations, focusing on weighted p-norm scalarizations and scalarizations based on a weighted norms that are modifications of the weighted Tchebycheff norm. We study the structure of the different weight set decompositions and determine similarities and differences.

4 - Augmenting Biobjective Branch and Bound Using Scalarization-Based Information
Michael Stiglmayr, *Julius Bauß*

While branch and bound based algorithms are a standard approach to solve single-objective (mixed-)integer optimization problems, multiobjective branch and bound methods are only rarely applied compared to the predominant objective space methods. In this talk we propose modifications to increase the performance of multiobjective branch and bound algorithms by utilizing scalarization-based information. We use the hypervolume indicator as a measure for the gap between lower and upper bound set to implement a multiobjective best-first strategy. By adaptively solving scalarizations in the root node to integer optimality we improve both upper and lower bound set. The obtained lower bound can then be integrated into the lower bounds of all active nodes, while the determined solutions is added to the upper bound set. Numerical experiments show that both the number of investigated nodes and the total computation time are significantly reduced.

■ WB-08

Wednesday, 10:30-12:00 - 10.50 HS 102

Power Systems Planning and Optimization I

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Anil Kaya*

1 - Stochastic Optimization of Operational Flexibility of Hydroelectricity for Large-Scale Renewable Integration
Neng Fan

Different from wind and solar power generation, hydroelectricity has not only zero emission and low generation cost, but also high controllability and operational flexibility, enabling hydroelectric units to start up and increase their power output quickly to prevent power supply shortage risk resulting from contingency events or recover power grids from disturbance. This talk will adopt data-driven optimization approaches for the operations of hydroelectricity to enhance the reliability and resilience of power systems and to address climate change problems by promoting large-scale renewable energy integration. Through case studies and numerical experiments, this research will demonstrate the flexibility of hydroelectricity, and its benefits for large-scale renewable energy integration to modern power systems.

2 - Benders decomposition for energy system planning with multiple climatic years
Leonard Göke, *Mario Kendziorski*

Planning models of macro-energy systems evaluate technological options to cut emissions of energy supply. Especially wind and photovoltaic are key options but capturing their fluctuations within models is challenging. Ideally, representation should not only have high spatio-temporal detail, but account for different climatic years as well. At the cost of exponentially increasing problem size, single-stage scenarios can extend linear planning models and stochastically account for different climatic years.

To reduce solve time of stochastic planning models, we decompose the problem into a top part for capacity expansion and multiple sub-problems for operation in each climatic year and each year of planning. Applying the Benders algorithm, we iteratively solve the top- and sub-problems utilizing parallel computing.

To accelerate convergence of the algorithm, we introduce two refinements both limiting the solution space of the top-problem. First, a linear and static trust region that is derived from a heuristic solution of the model and is removed at a certain optimality gap to ensure optimality. Second, a quadratic and dynamic trust region that is formulated as a second-order cone constraint and restricts the problem to the neighbourhood of the current best solution.

Results show that the introduced refinements greatly improve convergence of the Benders algorithm and make planning with multiple climatic years practically viable.

3 - A generic optimization model for operational planning and bidding of production units and evaluation of flexibility in district heating systems
Daniela Guericke, *Amos Schledorn*, *Henrik Madsen*

District heating systems allow an efficient supply of heat while using the advantages of coupling it to other sectors, such as simultaneous power and heat production utilizing different energy carriers. Most district heating systems use several different types of units to produce heat. The technologies reach from natural gas and electric boilers to biomass-fired units as well as waste heat from industrial processes and solar thermal units. Furthermore, combined heat and power units (CHP) units are often included to exploit synergy effects of simultaneous heat and electricity production.

We present a generic network-flow based mathematical formulation for the operational production optimization in district heating systems. The model is formulated as a two-stage stochastic program to account for uncertainty resulting from electricity prices and renewable energy production. Furthermore, we show how the model can be used for determining bids for electricity markets and evaluation of demand-side flexibility in district heating systems. Our results are based on real data from district heating systems in Denmark with different requirements, which illustrates an application under real-world system configurations.

4 - Optimising Italian Electricity and Gas Sectors Coupling in a 2030 Decarbonized Energy System
Giovanni Micheli, *Maria Teresa Vespucci*, *Laura Tagliabue*, *Dario Siface*

In December 2019 the European Commission presented the new program "Green Deal", which defines the ambitious European strategy to mitigate climate change. According to the document, the European Commission aims at achieving climate neutrality in 2050 by cutting greenhouse gas emissions by 55% compared to 1990 levels by 2030. The power systems will be particularly involved in the transformation process due to the need for electrification and the development of renewables, especially non-programmable ones. The strong increase in renewable sources will also require major overhauls of flexible resources to comply with the secure operation of the system. Furthermore, as early as 2030, the first applications of the hydrogen vector and biomethane are considered to appear. These are the reasons why Power-to-Gas (PtG) technology is considered of large interest: it allows converting surplus renewable generation into gas fuel (hydrogen or biomethane), which can be stored locally to be used later or injected into the natural gas network. The deployment of PtG plants increases the interconnection between electricity and gas systems and requires new modeling tools to analyze all new interdependencies. The aim of this contribution is twofold: (i) to present a novel medium-term simulation tool for the operational planning of integrated systems with bi-directional energy conversion; and (ii) to present the results of the application of this tool to a case study focused on Italy challenges exploring the decarbonization pathways. The tool developed simulates the simultaneous operation of the power and of the gas systems to supply the demand for electricity and gas at minimum total cost, with an hourly detail and while respecting all the technical constraints of the considered systems.

■ WB-09

Wednesday, 10:30-12:00 - 10.50 Raum 604

OR approaches for sustainability

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Magnus Fröhling*

1 - Balancing preferential access and fairness with an application to waste management in Bavaria

Bismark Singh, *Christian Schmitt*

Typically, within facility location problems, fairness is defined in terms of accessibility of users. However, for facilities perceived as undesirable by communities hosting them, fairness between the usage of facilities becomes especially important. Limited research exists on this notion of fairness. To close this gap, we develop an optimization framework for the allocation of populations of users to facilities such that access for users is balanced with a fair utilization of facilities. The optimality conditions of the underlying models provide a precise tradeoff between accessibility and fairness. We define new classes of fairness, and a metric to quantify the extent to which fairness is achieved in both optimal and suboptimal allocations. Special cases of our general models reduce to the classical notion of proportional fairness. Computationally, the underlying mixed-integer quadratic optimization models are challenging to solve naively for medium-sized instances. We propose several enhancements that facilitate a feasible solution, and develop a heuristic that does not require solving an optimization model. Our work is motivated by pervasive ecological challenges faced by the waste management community as policymakers seek to reduce the number of recycling centers in the last few years. Applying our models on data for the state of Bavaria in Germany, we find that even after the closure of a moderate number of recycling centers, large degrees of access can be ensured provided the closures are conducted optimally. Fairness, however, is impacted more, with facilities in rural regions shouldering larger loads of visiting populations than those in urban regions.

2 - A Solution Approach for the Multi-Objective Green Flexible Job Shop Scheduling Problem with Dynamic Energy Tariffs

Sascha C Burmeister, *Daniela Guericke*, *Guido Schryen*

Rising costs for energy are increasingly becoming a vital factor for the production planning of companies. To reduce energy costs and at the same time increase the environmental sustainability of production, large energy consumers can use dynamic energy tariffs. With dynamic energy tariffs, the energy costs may be indicated by a cost curve to reflect, for example, CO2 emissions or the energy mix, to encourage renewable energy consumption. In this way it is possible to promote the consumption of renewable energies (e.g., wind or photovoltaic) in case of oversupply or vice versa to reduce it in case of low renewable energy production. 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. Recent studies provide multi-objective approaches to model the trade-off of minimizing makespan and energy costs. However, the literature is limited to coarse-grained time periods and does not consider dynamic tariffs whose costs change at short intervals, so that production schedules may fall short on energy costs. We aim to close this research gap by considering frequently changing energy costs. We propose a multi-objective algorithm based on the Non-dominated Sorting Genetic Algorithm (NSGA-II) with both makespan and energy cost minimization as the objectives. We evaluate our approach by conducting a computational study using prominent FJSP-benchmark instances from the literature, which we supplement with a dynamic energy tariff. To investigate the trade-off between a short makespan and low energy costs, we present solutions on the approximated Pareto front and discuss our results.

3 - Eco-energy-efficient simultaneous lot-sizing and scheduling: a tri-criteria problem

Markus Hilbert, *Andreas Dellnitz*, *Andreas Kleine*

In the context of lot-sizing and scheduling, minimizing energy consumption is a typical criterion to improve a company's ecological footprint. In the literature, trade-offs between energy consumption and some economic criterion (e.g., energy costs) are analyzed. However, indirect carbon dioxide emissions are also an important aspect for the ecological footprint of a company. One might deduce that minimizing energy consumption also minimizes the indirect emissions of a company. In this talk, we show that such a positive one-to-one relationship needs to be questioned under time varying energy prices. Here, based on an instance of a tri-criteria simultaneous lot-sizing and scheduling problem, we determine the three-dimensional Pareto front via the elastic constraint method to demonstrate that all three criteria - time-dependent energy costs, energy consumption and corresponding carbon dioxide emissions - are conflicting. Due to the potential conflict between the three objectives, we refer to the tri-criteria optimization problem as eco-energy-efficient simultaneous lot-sizing and scheduling.

4 - A tool for spatial Multi-Criteria Decision Analysis: Application to a sustainability and a suitability case study for energy systems in Switzerland

Matteo Spada, *Peter Burgherr*

The increased availability of spatial data, together with a deeper awareness about the importance of the spatial dimension to support decision-making have highlighted both the central role and the key directions for planning and management across many domains. In this context, spatial Multi-Criteria Decision Analysis (sMCDA) has become a useful method, since it combines MCDA with Geographical Information System (GIS) and it is applicable to different topics. The MCDA enables to consider a wide variety of aspects, e.g., environmental, socio-economic, etc., in a transparent manner, while GIS accounts for the spatial variability of the problem. This study presents a new tool for sMCDA problems, the sMCDA Tool. It aims to provide a practical and straightforward guide to assess MCDA at the spatial level, combining an intuitive Graphical User Interface (GUI) with advanced visualization capabilities and the possibility to export and print the results. In this version, the sMCDA Tool considers definite or uncertain inputs and can run two different types of MCDA methods: i) weighted sum and ii) ELECTRE-TRI. In both cases, the tool can run a Stochastic Multi-criteria Acceptability Analysis (SMAA) approach for uncertainty quantification. To demonstrate the potential of the proposed tool, two applications are provided. First, a sustainability assessment for Deep Geothermal Energy (DGE) systems, and second, an evaluation of the suitability of proposed sites for Carbon Capture and Sequestration (CCS). For both case studies, the results will be presented for different hypothetical stakeholders in Switzerland.

■ WB-10

Wednesday, 10:30-12:00 - 20.30 SR 0.014

Distribution problems and reduction of CO2 emissions

Stream: Logistics
Invited session
Chair: *Okan Dukkanci*

1 - Planning Sustainable Routes: Economic, Environmental and Welfare Concerns

Okan Dukkanci, *Ozlem Karsu*, *Bahar Yetis Kara*

This study introduces a problem called the Sustainable Vehicle Routing Problem in which the sustainability notion is considered in terms of economic, environmental, and social impacts. Inspired by real-world problems that large cargo companies face for their delivery decisions, we present a new vehicle routing problem by considering the welfare of all three stakeholders of the problem: an environmentally conscious company, the drivers, and the customers. Thus, the proposed problem consists of three objective functions. The first one is to minimize the total fuel consumption and emission to represent the companies' main economic and environmental concerns. The second one is to maximize the total welfare of the drivers through a function that encourages equitable payment across drivers while encouraging low total driver costs. The third one is to maximize the total welfare of the customers through a function that encourages fairness in terms of delivery times. The last two objectives are measured using slots for tour lengths and delivery times. We implement an efficient solution approach based on the ϵ-constraint scalarization to find the nondominated solutions to our tri-objective optimization problem. The talk will present computational results that provide insights into the trade-off between the objectives.

2 - Economic Viability of Mobile Deconsolidation Points in the Distribution of Perishable Goods

Michaela Thulke, *Thomas Volling*, *Karsten Kieckhäfer*

In this contribution, we study the economic viability of mobile deconsolidation points (MDPs) in the distribution of perishables in comparison to traditional milk-run deliveries. The research is motivated by the need to reduce waste while maintaining a high service level and the need to mitigate ecological issues in distribution logistics (e. g., greenhouse gas emissions) as well as social issues pertaining to traffic volume, congestion, noise, etc. In this context, we model MDPs as containers or semi-trailers that are shipped from central warehouses to urban areas. They hold goods consolidated to full truckloads to serve nearby demand clusters, thereby allowing for inventory pooling. From the MDPs, the goods are transshipped to their destination in small

quantities with eco-friendly vehicles. This structure is derived from established concepts in parcel services with an additional focus on inventory pooling to reduce waste of resources and stock-out risk. To minimize the holding and shipping cost in such a type of distribution network, we develop a closed-form solution that combines a newsvendor model for optimal inventory decisions with a continuous approximation approach to estimate resulting shipping costs. After validating that the approximation yields results with a maximum gap of 10 % above the optimal solution, we analyse different network structures to identify conditions in which MDPs allow for reduced operational costs compared to milk-run deliveries. According to the analysis, MDPs offer an economically viable way to counteract the waste of resources especially in dense networks with large clusters.

3 - Improving the Operational Efficiency and Reducing Transport Related Carbon Emissions of Food Distribution Hubs
Arijit De, Barbara Tocco, Matthew Gorton

Small-scale food producers suffer from low margins and weak bargaining power. Food hubs, which aggregate products from such producers and deliver to final consumers, may improve producers' economic fortunes and contribute to local economic development. However, food hubs often involve small volume journeys, increasing the logistics cost, with carbon emissions potentially exceeding those of supermarket-based supply chains. This research seeks to improve the food hub's operational and environmental efficiency in logistics by minimizing transport costs and carbon emissions. The study addresses 'producer-to-hub-to-customer' distribution problem where products are shipped on the following links - producer groups to hub, producer groups to customer zones and hubs to customer zones. A mathematical model is developed to address the problem while seeking to minimize total costs comprising of transportation and fuel costs while aiming to fulfill customer demand. The model mitigates the carbon emission and fuel consumption on shipment links and reduces the vehicle trips and unused volume of vehicle types, thereby enhancing operational efficiency. Application of the model draws on real-world data for a local food hub serving over 150 producers in the North East of England. Experiments consider the extent to which co-operation between producers in delivering to the hub alters transport and fuel costs as well as carbon emissions. In addition, the study examines the impact of fuel price variation and demand fluctuation on cost components and carbon emission. Useful insights are obtained after investigating the effects of shipment delay and disruptions on shipment links. The analysis also considers the effect on costs and carbon emissions of switching to electric vehicles.

4 - Benefits of Proactive Transshipments for an Automotive Manufacturer under Emission Constraints
Bastian Vorwerk, Christian Weckenborg, Thomas Spengler

The high number of transports in industry causes a significant proportion of the emissions that need to be reduced regarding global warming. A part of the transports is caused by lateral transshipments, which occur when parts are distributed among different locations within one echelon for various reasons. To be able to reduce the number of transports, proactive transshipments can be used. In proactive transshipment models, parts are transshipped at predetermined points in time before the demand occurs. In the scientific literature, the consideration of emissions, as well as a differentiation of vehicle types, are neglected in planning approaches to proactive transshipments. Our planning approach adopts emission limits and provides a detailed consideration of different vehicle types for the execution of transshipments. We decide about the types and amount of vehicles used between locations in different periods. This planning approach is specified for the prototype production of automotive manufacturers. A case study based on automotive manufacturer data is presented, comparing the costs and emissions between proactive and reactive transshipments with and without emission limits. We find that emission limits can influence vehicle type selection and the products to be transshipped during proactive transshipments.

■ WB-11

Wednesday, 10:30-12:00 - 10.50 Raum 602

Economic dynamics and markets

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Emil Kraft*

1 - Pricing Optimal Outcomes in Coupled and Non-Convex Markets: Theory and Applications to Electricity Markets
Johannes Knörr, Mete Seref Ahunbay, Martin Bichler

Classical results in general equilibrium theory assume divisible goods and convex preferences of market participants. In many real-world markets, participants have non-convex preferences and the allocation problem needs to consider complex constraints rendering the welfare maximization problem a non-convex optimization problem. Electricity markets are a prime example. Walrasian prices are impossible in such markets, yet linear and anonymous prices are important as price signals for futures markets and investment decisions. Heuristic pricing rules based on the dual of the relaxed allocation problem are used in practice today. However, these rules have been criticized as they lead to very high out-of-market side-payments and inadequate congestion signals. We show that existing pricing heuristics optimize specific design goals that can be conflicting. The trade-offs can be substantial, and we establish that the design of pricing rules for non-convex electricity markets is fundamentally a multi-objective optimization problem. In addition to traditional weighing techniques, we introduce a novel parameter-free pricing rule that minimizes incentives for market participants to deviate locally. Our theoretical and numerical findings show how the new pricing rule capitalizes on the upsides of existing pricing rules under scrutiny today. In particular, we show that we can compute prices that incur very low make-whole payments while providing adequate congestion signals and low lost opportunity costs. Our suggested pricing rule does not require weighing of objectives, it is computationally scaleable, and balances trade-offs in a principled manner, addressing an important policy issue in U.S. and European electricity markets.

2 - Mathematical Optimization for Analyzing and Forecasting Nonlinear Network Time Series
Milena Petkovic, Nazgul Zakiyeva

This work presents an innovative short to mid-term forecasting model that analyzes nonlinear complex spatial and temporal dynamics in large-scale energy networks under demand and supply constraints using Network Nonlinear Time Series (TS) and Mathematical Programming (MP) approach. We address three challenges simultaneously, namely, the adjacency matrix is unknown; the total amount in the network has to be balanced; dependence is unnecessarily linear. We will use a nonparametric approach to handle the nonlinearity and estimate the adjacency matrix under sparsity assumption. The estimation is conducted with the Mathematical Optimisation method. We illustrate the accuracy and effectiveness of the model on the example of the natural gas transmission network of one of the largest transmission system operators in Germany, Open Grid Europe. The proposed model can be used to support optimal decision planning and efficient network operation by reducing financial and technical risks in the energy transmission networks such as natural gas, electricity, and renewable energy, as well as in other distribution networks like water distribution. Prediction power and interpretation of the complex network dynamics represent a crucial component of intelligent control of the energy networks to reach the security of supply and climate targets of the European Green Deal in a cost-effective and competitive way.

3 - A Bicriteria Almost Equal Minimum Cost Flow Model For Day-Ahead Trading
Till Heller, Elisabeth Finhold, Sven Krumke, Neele Leithäuser

As the share of renewable energy and therefore the fluctuation in power generation increases, using a battery to market the power saved / used by a flexible process becomes more and more important and attractive. The charging and discharging process of a battery can be modeled as a flow model in a time-expanded graph where distinguished nodes that describe the battery states at different points in time are given. We model the costs for this process as edge costs between nodes that correspond to consecutive points in time. An optimal battery strategy can now be obtained by computing a minimum cost flow in the given network graph. If the charging and discharging of a battery takes place as a coupled process of a production process, a steady and even charging and discharging is often important. In this paper, we describe a bicriteria flow model based on the Almost-Equal-Minimum Cost Flow Problem (AEMCFP) in which both trading profits and a steady flow of energy are considered as the two objectives. In the AEMCFP one is given additional sets of edges on which the flow values differ at

most by a given constant. Given such a fixed constant, we obtain a strongly polynomial algorithm based on a parametric search approach. We present a case study for bidding on selected days in the German day-ahead market.

■ WB-12

Wednesday, 10:30-12:00 - 10.50 Raum 701.3

Transport in Transition: Coupling transport and energy systems

Stream: Mobility and Traffic
Invited session
Chair: *Patrick Jochem*

1 - Scheduling electric vehicles by Simulated Annealing with recombination through ILP

Han Hoogeveen, Wouter ten Bosch, Marcel van Kooten Niekerk

We consider the Electric Vehicle Scheduling Problem (e-VSP): a set of trips corresponding to a given time-table have to be driven by a set of electric buses with limited capacity. This problem, like many other planning problems, boils down to assigning to each bus a subset of the trips with the obvious side-constraint that the selected subset can be feasibly driven by this single bus; such a feasible subset is called a (vehicle) task then. If we know all possible tasks, then we can select the best set of tasks by solving an ILP. This idea has inspired many researchers to the heuristic of finding a decent subset of all tasks using the technique of Column Generation and then solve the ILP. For the e-VSP this approach leads to reasonable solutions, but there is still room for improvement. Instead of using Column Generation, we present a new solution approach by applying Simulated Annealing to find the subset of tasks that we use as input for the ILP. For the e-VSP this leads to far better solutions. Moreover, our approach is generally applicable and has as a clear advantage that we do not have to solve the pricing problem anymore, which increases the application possibilities.

2 - Lifted Inequalities for the Refueling Station Location Problem with Routing

Paul Göpfert, Stefan Bock

In order to leverage a widespread use of electric vehicles, an appropriate charging infrastructure is necessary for long distance demands. The Refueling Station Location Problem with Routing (RSLP-R) is an optimization problem that tries to address this challenge by selecting a limited set of stations from a candidate set. The aim of the problem is the maximization of demand coverage. A station set covers a demand, if a driver can reach its destination without a violation of the imposed range and deviation restrictions. Recent promising Branch-and-Cut approaches to this problem shift this complicating routing aspect into the cut separation routines. However, the basic inequalities of these approaches address only one demand at a time. In this talk, we introduce further valid inequalities for the RSLP-R that consider a small set of demands simultaneously. Furthermore, we exploit the fact, that more than one charging stop might be necessary to properly cover a demand. We use the well known lifting technique in order to obtain a valid inequalities for the full candidate set from valid inequalities for a proper subset of all candidate stations. The proposed separation routines also try to find a lifting sequence that maximizes the violation of the new cuts. Computational results on two real world road networks underline the strength of the inequalities and the efficiency of the separation algorithms.

3 - A multi-criteria assessment framework for zero-emission vehicles from a customers' perspective

Paul Fabianek, Reinhard Madlener

Based on economic and user-relevant criteria this paper proposes an assessment framework for zero-emission vehicles, using the Analytic Hierarchy Process approach for a Multi-Criteria Decision Analysis. The framework allows for a transparent evaluation of different zero-emission vehicles from the (potential) customers' perspective, without their direct involvement. The relevant criteria for the evaluation were derived from literature and seven semi-structured interviews with individuals who have driving experience with both battery electric and fuel cell electric vehicles. Seven criteria are found to be particularly relevant for the evaluation of zero-emission vehicles: total cost, range, charging or refueling time, charging/refueling infrastructure availability, greenhouse gas emissions, spaciousness, and driving dynamics. The assessment framework comprises value scores that represent the degree to which a specific zero-emission vehicle satisfies a given quality criterion and combines them with the weights derived in the Analytic Hierarchy Process. The results point to the particular importance of greenhouse gas emissions. Range, charging/refueling infrastructure availability, and charging/refueling time have medium importance. The framework seems useful for zero-emission vehicle design by car manufacturers and infrastructure operators and mobility providers in the field of battery electric and hydrogen mobility.

4 - A new flow-based location and capacity model for profit-oriented refueling station network transformation

Tjard Bätge, Christian Weckenborg, Thomas Spengler

The availability of refueling stations for alternative fuels is of high importance for the penetration of alternative fuel vehicles (AFV) in today's markets and is an important lever for sustainable mobility. Therefore, refueling station network deployment strategies are currently of great interest to researchers. Several quantitive location models have been specifically developed, adapted, and applied to determine optimal refueling station locations and network build-up strategies for AFV refueling from an overall system's perspective. However, the network operator's intrinsic economic objectives and its preference for transforming the existing refueling station network rather than building up new refueling stations are subordinate in most research. That is why a new formulation of a flow-based location model is introduced in this study that not only decides on the locations of new alternative refueling stations but also on the provisioned capacities of multiple fuel types at each newly opened and each already existing refueling station in a multi-period planning horizon. This new approach uses a profit-oriented, cash flow-based objective function to transform the existing refueling station network over time. A case study depicting northern Germany is presented to validate the new model and the computational results are discussed.

■ WB-13

Wednesday, 10:30-12:00 - 20.30 SR -1.025

Optimization Solvers

Stream: Software Applications and Modeling Systems
Invited session
Chair: *Daniel Junglas*

1 - Scalable Optimization in the Cloud with GAMS and GAMS Engine

Stefan Mann, Frederik Proske, Michael Bussieck

The common type of infrastructure to run GAMS models on for most users was and is their laptops or local workstations. This approach works, but has some limitations, which become more apparent as model sizes increase, or the number of model users increases. To overcome the lack of scalability of local computers, many users have begun to implement their own cloud based solutions around GAMS, but this requires a substantial investment in time and resources to implement.

To fill this gap we have recently developed a Kubernetes based, scalable and cloud native solution to solve GAMS models, which we call GAMS Engine. Engine scales both horizontally (many parallel instances), and vertically (instances can grow to TB of memory and 100s of CPUs). Engine also includes a job scheduler, quota and permission management.

In this presentation we will describe how we implemented the solution and how it is different from more traditional uses of Kubernetes. We will also talk about how GAMS Engine enables customers to fully automate their business optimization processes with little development effort.

2 - What's New in Gurobi 9.5

Mario Ruthmair

We give an overview of recent enhancements, new features, and performance improvements in our Gurobi 9.5 release. From the features

introduced in Gurobi 9.5, we discuss different SOS constraint encodings, a new heuristic for non-convex MIQCP, general constraints for norms, a deterministic work limit, a memory limit parameter, several callback enhancements, and new parameters for the integrated tuning tool.

3 - What's new in FICO Xpress Solver?
Daniel Junglas

We will present the latest developments in the FICO Xpress Solver for mixed-integer linear and nonlinear problems. This includes performance improvements as well as new solver features.

4 - Modern ML Ops with IBM CloudPak 4 Data
Alex Speil

Managing successful data science or decision optimization projects encompasses far reaching consequences.The requirements to embedding data science process well into a larger organization and connecting it seamlessly with the wider stakeholder audience have become more numerous and crucial. No wonder then, that over 50% of models never see the light of day and many projects fail or take years to be finally implemented. Long gone are the times when pure model building was the hardest part of getting things right. Today's AI projects need to be fair, robust, privacy conscious, explainable and transparent. Achieving that takes people from multiple backgrounds being tightly involved in a highly repeatable and continuous process. That means from very start of collecting and refining data to deploying models, monitoring and complying with regulations. IBM's CloudPak for Data provides the all encompassing underlying software infrastructure to the data (science) lifecycle. It supplies that tools necessary to manage and integrate the wider processes and roles behind it. In this way it replaces single purpose solutions that can be cumbersome to plug together, access, manage etc. and gives us the ability to do it all from one interface and one solution without unnecessarily moving the data. As a consequence it speeds up development tremendously by making data scientists, modellers, stewards and engineers focus on the task at hand and not distract themselves with making the tools work. All that while still staying open source based and extensible. In this talk, I want to give an overview of common pitfalls of ML development and MLops, how IBM's CloudPak for Data can help organizations get through these issues unscathed and scale successfully.

■ WB-14

Wednesday, 10:30-12:00 - 10.50 Raum 702

Ridesharing & pedestration

Stream: Mobility and Traffic
Invited session
Chair: *Miriam Stumpe*

1 - One-to-One Taxi-Ridesharing Systems
Miriam Stumpe, Peter Dieter, Guido Schryen, Oliver Müller, Daniel Beverungen

Taxi ridesharing systems (TRS) are considered one means towards more sustainable transportation by increasing car occupancy rates and thereby significantly improving the efficiency of urban transportation systems. In this study, we consider the one-to-one TRS approach, which is characterized by joint pick-up and drop-off locations for all customers of a shared trip; i.e., customers might be required to walk a short distance from their origin/to their destination.

Several approaches in the literature account for the one-to-one TRS by showing its advantages over other TRS variants, including shorter travel times, which promise greater customer satisfaction, as well as lower fuel consumption and emissions. However, most of these studies apply heuristics and make unrealistic assumptions about information availability. We contribute to closing this research gap by (1) suggesting a new mathematical model for a general conceptualization of the one-to-one TRS, (2) implementing a rolling horizon re-optimization approach and (3) performing extensive experimental studies based upon empirical data of the cities of New York and Porto and with varying assumptions about customer behavior (exogenous parameters) in order to evaluate different (endogenous) parameter settings for the TRS design. We show that (both exogeneous and endogenous) TRS parameter values have a great influence on the total savings of traveled distances achieved through a one-to-one TRS. Furthermore, we derive guidelines for practitioners who plan to implement a TRS.

2 - Microsimulation-based pedestrian flow planning during the FIFA World Cub in Qatar
Knut Haase, Simon Rienks, Usama Dkaidik

This year's FIFA World Cup will be held in Qatar. For the first time, all games will be played in just one city (Doha). In the preliminary round, four group matches take place daily, for which eight stadiums are available. In order to be able to cope with the enormous traffic flows before and after the games, a metro with three lines and two central interchange stations was built in Doha. Due to the game schedule, overlapping passenger flows are to be expected between the games, i.e. the traffic flow of spectators leaving one stadium may cross those that are on their way to another. In order to avoid critical densities in the subway stations, especially in the main stations, a mathematical model for controlling the access flows is presented. The pedestrian flows to be expected within the subway stations are analyzed using a microsimulation (social force model). Depending on the results, the mathematical planning model is then calibrated (feedback) so that smooth flows of people in the stations are made possible in the planning.

3 - Impact of public lighting on passengers' modal choice for nocturnal transportation
Elodie Bebronne, Sabine Limbourg

Artificial light at night has many ecological consequences, including attracting or repelling certain animals. Dark corridors have been implemented in several regions to preserve or restore an ecological network conducive to nocturnal wildlife, maintain the quality of the night sky, and protect human health. These dark corridors are land-use plans that aim to reduce or delete specific light points and create paths of darkness, allowing for the movement of nocturnal species. As such, these corridors help preserve biodiversity and reduce energy consumption. However, they can also induce a sense of insecurity and modify the modal choice of night-time travel. In order to analyse the impact of public lighting on Walloons, we conducted a survey. This questionnaire has been completed by 685 citizens (allowing us to reach a 3.74% error margin, with a 95% confidence level). Our study enabled us to determine the evolution of the feeling of safety in different contexts and lighting conditions, the changes in modal split, and the acceptance of lighting reduction policies, respondents being or not aware of light pollution. Our results should help decision-makers determine appropriate policies in land-use management and, more specifically, public lighting.

■ WB-15

Wednesday, 10:30-12:00 - 10.50 HS 101

Discrete Optimization Problems I

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Christina Büsing*

1 - Optimized Production Planning in Cable Manufacturing
Sarah Drewes

Optimized Production Planning in Cable Manufacturing

We automated and optimized the daily production planning process for a cable manufacturing company using MILP (Mixed Integer Linear Programming). Before, production planning was done manually, which required several hours each day for different machines and often led to sub-optimal solutions, causing excessive cost for waste materials.

Each day, raw material on spools of different lengths need to be combined and cut to cables such that leftover material is minimized. Either a target cable length is given, or the total produced cable length is to be maximized. Additional requirements are necessary to make the solution feasible for production, e.g., a lower bound per cut and limitation of the number of total cuts. The problem can be interpreted as an extension of a lot sizing of cutting stock problem, with unknown demand per period or flexible cut length, and where in each lot or cut, three items need to be combined to one product. This planning problem needs to be solved each day with new input data for different machines.

We are going to present the statement of this problem as an MILP and how we modeled different production requirements. We show how we reformulated the problem for performance to meet time requirements. We used MATLAB Optimization Toolbox for modeling and solving

the MILP. The model was made available to the production planners via a simple MATLAB user interface, that allows them to interactively use the mathematical model in their daily planning.

Automation and optimization of this planning process reduced planning time and effort by 50-70% and significantly reduced waste material, leading to annual savings of about 400.000 CHF.

2 - New lower bounds for the double row facility layout problem

Frank Fischer, Anja Fischer, Angelika Wiegele

The Double Row Facility Layout Problem (DRFLP) aims for arranging machines along two sides of a path such that the machines do not overlap and the weighted sum of the pairwise distances is minimized. In contrast to the single row version of the problem (SRFLP), an optimal solution may contain gaps between adjacent machines. This makes a direct generalization of optimization models for the SRFLP to the DRFLP difficult. In this talk we present a new approach to combine the most successful models for the SRFLP with a new approach to handle the local arrangements of adjacent machines including their gaps. Indeed, the SRFLP model based on betweenness variables is used to model the distances between machines that are arranged with a relatively large distance between them, whereas machines that are arranged close to each other are modelled by solving exact subproblems consisting only few machines. This approach does not solve the DRFLP exactly but aims at computing good lower bounds on the optimal solution value. We present some first numerical experiments.

3 - The Effects of Closest Assignment Constraints on the Complexity of Capacitated Facility Location Problems

Sophia Wrede, Christina Büsing, Timo Gersing

Capacitated Facility Location Problems with Closest Assignments (CFLP-CA) are an extension of the well known, strongly NP-complete Capacitated Facility Location Problem (CFLP). With this extension, we recognize that not just facilities have demands on what a solution is supposed to look like. We also acknowledge that customers have specific requests on a solution; in this case, they have a strong preference towards their closest facility.

In this talk, we show that finding a feasible solution for the CFLP-CA is already strongly NP-complete if the underlying graph forms a star. On paths and cycles, however, the problem can be solved efficiently - contrary to the CFLP. This is due to special combinatorial structures enforced by the Closest Assignment constraints which become exploitable on graphs with node degree of at most two. We use these combinatorial structures in a polynomial-time algorithm to solve CFLP-CA-instances on paths and explore how this algorithm can be adapted for solving instances on cycles.

4 - Serving stochastically-departing customers: Near-optimal adaptive policies

Danny Segev, Ali Aouad

Suppose we are given a finite collection of customers, to be potentially served across a discrete planning horizon. In each time period, our policy may serve at most one customer, earning his/her associated profit. Following this choice, each available customer independently departs with some time-invariant individual probability. Our objective is to propose a service policy whose expected total profit is maximized.

When competing against the optimal adaptive policy, the current best approximation guarantee in polynomial time was attained by Cygan, Englert, Gupta, Mucha, and Sankowski [ITCS '13]; their LP-based policy is known to perform within factor 0.701 of optimal. This talk will describe a very natural approach to tackling this problem, combining appropriate parameter rounding and dynamic programming. The performance of this approach will be analyzed via coupling-based ideas, showing how to obtain a (1-eps)-approximate adaptive policy in quasi-polynomial time.

■ WB-16

Wednesday, 10:30-12:00 - 20.30 SR -1.012

Problems with linear and piecewise linear functions

Stream: Continuous and Global Optimization
Invited session
Chair: *John Warwicker*

1 - A spatial branch-and-bound algorithm with polyhedral underestimators for nonconvex piecewise-linear optimization

Thomas Hübner

We study optimization problems with nonconvex separable piecewise-linear functions (PLFs). These NP-hard problems are usually solved by mixed-integer linear programming solvers that use multiple binary variables to reformulate the PLFs. In contrast, we approach the problem from the perspective of global optimization. Thereby, we use an algorithm from computational geometry to compute the lower convex envelope of a PLF over a hyperrectangle. By considering the envelope as a polyhedral underestimator, we obtain a linear-programming-based relaxation that is used to compute lower bounds in a convergent spatial branch-and-bound algorithm. Finally, we compare this algorithm with existing mixed-integer approaches in terms of their theoretical properties and computational performance.

2 - Generating Optimal Robust Continuous Piecewise Linear Regression with Outliers Through Combinatorial Benders Decomposition

John Warwicker, Steffen Rebennack

Using piecewise linear (PWL) functions to model discrete data has applications for example in healthcare, engineering and pattern recognition. Recently, mixed-integer linear programming (MILP) approaches have been used to optimally fit continuous PWL functions. We extend these formulations to allow for outliers. The resulting MILP models rely on binary variables and big-M constructs to model logical implications. The combinatorial Benders decomposition (CBD) approach removes the dependency on the big-M constraints by separating the MILP model into a master problem of the complicating binary variables and a linear subproblem over the continuous variables, which feeds combinatorial solution information into the master problem. We use the CBD approach to decompose the proposed MILP model and solve for optimal PWL functions. Computational results show that vast speedups can be found using this robust approach, with problem-specific improvements including smart initialisation, strong cut generation and special branching approaches leading to even faster solve times, up to 1,500 times faster than the standard MILP approach.

3 - A note on matrix reordering for linear system solutions by iterative methods in interior point methods

Marta Velazco, Wellington Rodrigues, Aurelio Oliveira

In this work, the linear systems arising from interior point methods for linear programming are solved using the preconditioned gradient method. Two preconditioners are adopted. The controlled Cholesky factorization of the normal equations system is used in the first iterations and de splitting preconditioner is used in the final ones. The controlled Cholesky factorization performance depends upon the previous ordering of the linear programming constraint matrix rows. A comparison among different reordering methods is performed in order to verify the one more suitable for this approach. Variants of the nested dissection and minimum degree are among the considered heuristics. Computational experiments with large-scale linear programming problems from several collection sets are performed in order to determine the heuristic of choice for such particular approach.

4 - Using neural networks to solve linear bilevel problems with unknown lower level

Ioana Molan, Martin Schmidt

Bilevel problems are used to model the interaction between two decision makers in which the lower level optimization problem, the so-called follower's problem, appears as a constraint in the upper-level problem of the leader. One issue in many practical situations is that the follower's problem is not explicitly known by the leader. For such bilevel problems with unknown lower level we propose the use of neural networks to learn the follower's optimal response to given upper-level decisions from available historical data of pairs of leader and follower decisions. Integrating the resulting neural network in a single-level reformulation of the bilevel problem then leads to a challenging black-box constrained model. For these models, we exploit Lipschitz optimization techniques to solve this reformulation. In this talk, we discuss the details of this approach and show its applicability by a numerical case study.

■ WB-17

Wednesday, 10:30-12:00 - 20.30 SR -1.011

Emergency Medical Services

Stream: Health Care Management
Invited session
Chair: *Melanie Reuter-Oppermann*

1 - Evaluation of EMS Location Models using Response Time Distribution Functions and (Conditional) Value at Risk

Isabel Wiemer, Matthias Grot, Brigitte Werners

When evaluating the sites for ambulances of emergency medical service (EMS) in a stochastic context, often only the expected coverage value is considered. However, a comparison of the total distribution functions of response times of all emergency calls can provide additional information. In financial mathematics, performance criteria like value-at-risk (VaR) and conditional value-at-risk (CVaR) are used for uncertain situations. Such approaches have hardly been applied to the context of EMS. Therefore, we propose to evaluate strategic EMS location planning decisions using the total distribution functions of response times of all emergency calls. We use a current stochastic location planning model and apply varying model objectives, such as expected coverage for different response times and fairness. In this way, we achieve several optimal solutions. To obtain the respective distribution function of all response times, we perform a discrete event simulation for each solution. It is based on the optimized site locations and ambulance allocations as well as anonymized real world data of a local EMS provider. The case study demonstrates that the distribution function as well as VaR and CVaR provide valuable information about the consequences of a solution. In contrast to the expected coverage value for a given response time, the individual response time of every emergency call is considered. For a comparison of solutions, stochastic dominance, VaR and CVaR provide additional information and should therefore be used to evaluate strategic location planning models in the context of EMS.

2 - Time-dependent ambulance allocation for EMS decision support

Matthias Grot

A well-designed EMS system is essential for providing the best possible quality of care to patients in emergencies. Demographic changes or extreme weather conditions lead to a continuous increase in emergency calls. Because the number of ambulances and qualified personnel are limited, there is a constant need to optimize the use of the available resources in existing EMS systems. We provide a general approach for supporting decision makers at the tactical decision-making level of ambulance allocation and relocation. First, we analyze the given historical data to find suitable time periods that have similar structures in terms of the number of calls and the time of day itself. An extension of our Capacitated MEXCLP model is developed that additionally accounts for time-periods to incorporate the variations in emergency demand. Computational experiments are conducted for an existing EMS network structure to optimally allocate and relocate ambulances depending on the previously determined time-periods. A discrete event simulation is used to evaluate the model solutions and to provide further insights into the trade-off between quality and cost of care. Further, the benefits of additional flexible waiting sites are analyzed. Preliminary results, based on anonymized real-world EMS data, show that vehicle relocation and flexible waiting sites can provide considerable potential savings in the required number of ambulances in different time periods while maintaining a high level of coverage.

3 - Simulation-based location optimization of ambulance stations

Johanna Schneider, Michael Moos, Jennifer Werner, Neele Leithäuser

The structure of ambulance stations has grown historically in Germany. Step-by-step, outdated ambulance stations have to be renovated or newly built. This raises the question: Are the current locations optimal? We investigated this question for several neighboring ambulance stations in the regions Rhine-Hesse and Hunsrueck-Nahe, Germany. Therefore, we developed data-based methods to find promising combinations of potential stations and to evaluate those scenarios in a static and dynamic way. The main methods will be presented in this talk. Based on data of real rescue operations and a detailed road network, we estimated a specific speed profile for ambulances driving with blue lights and sirens. Using this speed profile, we calculated the driving time from all potential and surrounding stations to every road segment. Having the complete driving time information, we solve a multicriteria integer model to find promising combinations of potential stations. We require every road segment to be covered within the allowed time and want to optimize different objective functions, e.g. the population reached within 5 minutes and within 10 minutes which are contradicting goals. This static optimization is important for the fulfillment of legal regulations, but in the highly dynamic world of emergency services, the ambulances are often occupied. Therefore, the best combinations are further investigated regarding the number of vehicles per station based on a concurrency analysis of the real rescue operations. Additionally, we simulate for each location and vehicle scenario the occurrence of the historic rescue operations over three years. This dynamic analysis gives a realistic estimation of driving times and workloads after a change in location structure or vehicle distribution.

■ WB-18

Wednesday, 10:30-12:00 - 20.30 SR -1.013

Urban delivery and mobility platforms

Stream: Logistics
Invited session
Chair: *Rossana Cavagnini*

1 - Autonomous Last Mile Delivery: The Effects of Using Transport Boxes

Anna Hess, Boris Amberg

We are developing and researching operational research methods for a last mile delivery logistics system that stores various freight in a central depot and uses autonomous delivery robots to pickup and deliver freight from and to customers. In this system the handover of freight can proceed as attended delivery and pickup, unattended delivery and pickup, and self-service by customer.

We conduct our research within the scope of a pilot project for a city in Germany.

The main difference to other concepts with robots, that are recently under investigation, is that this pilot project uses transport boxes with a docking mechanism.

Using transport boxes comes with some significant advantages for the service level, that can be provided to customers and therefore may raise acceptance for this kind of delivery concepts. However, using transport boxes leads to higher investment costs for the necessary hardware. Additionally, transport boxes have to be picked up from the customer after removing the freight, resulting in more trips of the autonomous delivery robots.

In general, the goal of this logistics system is to complete all jobs efficiently with the available robots and transport boxes. One goal in this system is to reduce necessary box movements required to complete all orders. A conflicting goal is the permanent availability of empty boxes for the customers in the service area. We implemented a network flow formulation to identify reasonable possibilities of reusing empty boxes for orders.

In our talk we will present the basic ideas of the last mile delivery system and show results of a simulation study, evaluating the effects of using transport boxes and optimizing the flow of transport boxes.

2 - The Demand-scenario-based District Cutting Problem for Postal Deliveries

Rossana Cavagnini, Michael Schneider, Alina Theiß

Cost-efficient routing of postmen is of major importance for companies like our industry partner Deutsche Post DHL Group (DPDHL). DPDHL clusters street segments of a city into districts and determines a tour within each district, all starting at the depot. The objective is to minimize the total travel time required by the postmen for completing their tours. Because the number of letters varies on different days of the week, we have different demand scenarios, characterized by the number of districts to form. DPDHL already solved the problem based on the most likely demand scenario. The resulting problem is called the standard-demand district cutting problem (SDDCP). Before starting the tour, each postman has to pick up the letters at the depot. The letters are already sorted with respect to the SDDCP solution on preparation tables, and the order cannot be changed on a daily basis. Motivated by the need of keeping the postmen workload balanced, we study the problem of modifying the district composition and the associated

tours for demand scenarios different from the standard one, which require either a smaller or a larger number of districts. We refer to this problem as the demand-scenario-based district cutting problem (DS-BCP). This problem can be seen as a vehicle routing problem with total travel time minimization, but because the letters are sorted according to the SDDCP solution, problem-specific constraints arise. Because standard solvers cannot find a feasible solution to realistically sized instances in reasonable runtimes, we propose an iterated local search returning good-quality solutions in short runtimes. Through an extensive sensitivity analysis, valuable managerial insights for practitioners are drawn.

3 - Understanding Drivers in Crowdsourced Delivery Services

Marlin Wolf Ulmer, Rosemonde Ausseil, Jennifer Pazour

Crowdsourced transportation by independent drivers is central to urban delivery and mobility platforms such as GrubHub, Roadie, or UBER. While utilizing crowdsourced resources has several advantages, it comes with the challenge that drivers are not bound to decisions made by the platforms. One common issue in practice is that drivers decline assignments of delivery jobs, e.g., due to the required travel detour, the expected tip, or the area a job is located. Declined jobs lead to inconveniences for the platform (ineffective assignments), the corresponding customer (delayed service), and also the drivers themselves (non-fitting assignment, less revenue). In this work, we show how understanding driver preferences by analyzing drivers' past decision making can alleviate these inconveniences. To this end, we propose a sequential decision process where at equidistant time steps assignments of jobs to drivers are made. Drivers' acceptances of jobs are uncertain to the platform and depend on a variety of factors. Drivers who accept the request from the platform are assigned, perform the corresponding job and reenter the system later looking for another assignment. Drivers declining the assignment idle for a limited time to wait for another request, but leave if no assignment can be made. Every acceptance and declining decision reveals information about the drivers' preferences, i.e., the probability of a specific driver to accept a specific future assignment. We carefully approximate driver acceptance probabilities based on observed behavior and use this information in our subsequent assignment decisions. We show that our approximation leads to overall more successful assignments, more revenue for platform and drivers, and less waiting for the customers to be served.

4 - Strategic Request Acceptance for a Dynamic Pickup and Delivery Problem with Auction-based Collaboration

Yannick Scherr, Margaretha Gansterer, Richard Hartl

We consider the problem setting of a less-than-truckload carrier serving stochastic customer requests, each with a pickup location, delivery location, volume, and revenue. Each request must be answered dynamically by accepting or rejecting it immediately. On the next day, the accepted requests are served in routes using a set of vehicles with limited load capacity and route duration. After the request acceptance phase and before the requests must be served, multiple carriers participate in a combinatorial auction to exchange a subset of requests among each other. After carriers place bids on bundles of requests, an auctioneer allocates the bundles to carriers in a cost-minimizing way and distributes the auction profits equally. We model the carrier's optimization problem of maximizing its profit 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 used for solving a dynamic version of the vehicle routing problem with pickups and deliveries. We design policies for strategically accepting requests while recognizing the outsourcing options provided by the auction. Computational results show that - by trading requests in an auction - carriers can accept more requests than they could feasibly serve on their own. The carriers' request acceptance decisions impact their individual profits and the overall collaboration savings. The largest benefits can be achieved if carriers agree on a rule that prescribes which kind of additional requests should be accepted.

■ WB-19

Wednesday, 10:30-12:00 - 20.30 SR 0.019

Machine Learning and Explainability

Stream: Analytics and Learning
Invited session
Chair: *Ralph Grothmann*

Chair: *Davina Hartmann*

1 - Unsupervised Machine Learning For Scenario Reduction

Janosch Ortmann, Julien Keutchayan, Mike Hewitt, Walter Rei

Many problems in operations research can be formulated in terms of stochastic optimisation: some quantity is to be maximised or minimised subject to some constraints which are only partially known in advance.

In order to approximate the distributions of the unknown parameters and formulate a deterministic optimisation problem, scenarios are used. In order to accurately model the underlying sources of uncertainty, a large number of scenarios may need to be generated, which leads to high computational complexity and may even render the problem numerically intractable to solve. This motivates the scenario reduction problem, which consists of finding a small subset of the scenario set while keeping the induced error at an acceptable level.

In this talk, I will present two new problem-based scenario reduction methods. In the first, unsupervised machine learning is used to create clusters of scenarios with common near-optimal solutions. The second seeks representative scenarios by minimising the solution discrepancy (the difference in objective values between the representative and the other members of a cluster).

I will also present numerical validation of our algorithms on a network design problem. I will demonstrate how grouping the scenarios in the decision space via the opportunity cost algorithm leads to a better understanding of potential compromise solutions, which in itself leads to a better grasp of the problem and potential solution approaches. Moreover, we obtain new upper and lower bounds and an analysis of the parameters in terms of the decision-based clusters.

In most instances, our algorithms are able to drastically reduce the computation time while obtaining an equivalent, and sometimes even better, quality of the solution obtained.

2 - A combined measure based on diversification and accuracy gains for forecast selection in forecast combination

Felix Schulz, Nathalie Balla, Thomas Setzer

Recent innovations in the field of forecast combination include integrated methods for forecast selection, weighting and regularization. The methods proposed in related articles first label whether or not forecasters should remain in the selection using information criteria from statistical learning theory. Depending on the selection status, the optimal weights of all forecasters in the sample are then used as baseline to shrink the weights either toward zero or the mean, with the degree of regularization determining the final selection of forecasters. In this paper, we propose a new information criterion reflecting the importance of diversification and accuracy gains in the selection of forecasters for integrated methods. In an iterative procedure motivated by forward feature selection, each forecaster is selected sequentially, while at each step the increase in accuracy and diversification due to the addition of a forecaster to the previous selection is measured. To quantify the increase in diversity, the multiple correlation coefficient is used, which captures the correlation between the previously selected forecasters and a candidate, where the lower the correlation between the candidate and the selection, the higher the gain in diversity for the combination. For the accuracy increase, the accuracy achieved by optimal weight combinations with the previously selected forecasters is compared with the accuracy after adding a candidate. A hyperparameter further enables the tradeoff between accuracy and diversification gains in the criterion. Simulation-based studies show scenarios in which our presented information criterion achieves advantages in out-of-sample prediction accuracy over previous criteria for selection by accounting for accuracy and diversification gains.

3 - Models for Explainable Optimization

Michael Hartisch, Marc Goerigk

While explainability has become a major research area in machine learning over the past years, in operations research and mathematical programming the comprehensibility of solutions is hardly every scrutinized. Likely due to the existence of explicitly stated models and well defined solution processes, experts have high confidence in the correctness and usefulness of found solutions. However, even understanding a mathematical model can quickly become a challenging task, especially for people not familiar with modeling techniques. Users with less mathematical and computer background, e.g. the planner using the optimization software and the workers in charge of implementing

the result, may consider the solver a black box. We present and experimentally validate a modeling framework that inherently provides an explanatory rule, trying to clarify the causal effect of occurring scenario and selected solution. By restricting the number of eligible solutions and providing an explanatory rule, e.g. in form of a decision tree, we shift the focus towards comprehensibility and transparency. Our experiments indicate that the costs of explainability can be small, i.e., only a small percentage of nominal performance needs to be sacrificed to find solutions that provide simple explanatory rules.

4 - Application of Efficient Resampling Algorithms to Imbalanced Semiconductor Wafer Bin Classification Problem
You-Jin Park

In many machine learning applications, classification is one of the important tasks. Most classification algorithms have been developed and applied under the assumption that the number of instances for each class is nearly balanced. However, if the conventional classification algorithms on the basis of this assumption are applied to the class imbalanced dataset, it may lead to incorrect classification results. So, one of the challenging tasks for standard machine learning algorithms is to resolve the class imbalance problem properly. Generally, the class imbalance problem refers to the problem in which the numbers of instances of certain classes are very small, while the numbers of instances of the remaining classes are relatively large in the training dataset. In this study, as data preprocessing tool, we propose two efficient resampling algorithms called IDAHO based on instance density and BOD based on noise-outlier detection and removal to enhance classification performances. Particularly, we apply IDAHO algorithm to two semiconductor wafer bin datasets and then adopt C4.5 decision tree, support vector machine (SVM), multi-layer perceptron neural network (MLP-NN), and Naïve Bayes (NB) classifiers for evaluation of IDAHO algorithm, and also apply BOD algorithm to the same datasets and evaluate the classification performances with using SVM classifier. Through the experiments, it is shown that the both algorithms outperforms the traditional resampling methods with respect to three classification performance measures (i.e., accuracy, F-measure, and G-mean) regardless of classification algorithms considered.

■ WB-20

Wednesday, 10:30-12:00 - 20.30 SR 0.016

Revenue Management for Logistics and Mobility

Stream: Pricing and Revenue Management
Invited session
Chair: *Matthias Soppert*

1 - Contracting Strategies for Price Competing Firms under Demand Uncertainty
Benny Mantin, You Wu, Anne Lange

We study interactions between two capacity-constrained asset providers (APs) and multiple logistics service providers (LSPs) who trade transport capacities on a spot market where the former compete over prices. Prior to entering the spot market, the APs and LSPs face demand uncertainty, which they can circumvent by negotiating a contract to secure sales and capacity, respectively. The two agents face a trade-off: if they contract too much capacity, this may lead the LSP to end up with excess supply when spot market demand is low, whereas the asset provider may end up missing out on potential profit when spot market demand is high. We study this setting via a two-stage game theoretical model. In the first stage, we model the negotiation process as a bilateral Nash bargaining game between an AP and an LSP. In the second stage, demand is realized and the spot market brings together the LSPs—who aggregate demand not satisfied through their negotiated capacity—and the APs—who bring their remaining uncontracted capacity. We solve the model backwards to arrive at the Nash subgame perfect equilibrium. We distinguish between two solution approaches: static spot prices and dynamic spot prices. In the former, the APs are short-sighted and take spot market demand as exogenously given. In the latter, they recognize the interdependence of spot demand and spot price. We demonstrate that the simpler, static approach is a fair approximation of the spot market. We characterize the optimal pricing strategies in the spot market and, assuming a uniformly distributed demand, we analyze the bargaining stage to characterize when a contract between an AP and an LSP enhances both agents' profits: when potential demand is low and when the LSPs charge a low margin for their services.

2 - A model-based approach to strategic demand management for attended home delivery
Katrin Waßmuth, Niels Agatz, Moritz Fleischmann

In recent years, e-commerce is continuously growing and new business models and services are entering the home delivery market. For example, in the case of e-grocery, on-demand startups promise 'instant' grocery delivery within a few minutes. This innovative service offering challenges many assumptions of existing fulfillment strategies. In this talk, we focus on attended home delivery, where the service provider and customer typically agree on a specific time window to ensure a successful delivery of the purchased goods. This step involves the customer directly in the service creation process. In managing the service offering, service providers thus face complex trade-offs between customer preferences and the efficiency of service execution. These trade-offs drive demand management decisions on various levels, from strategic design decisions to operational real-time control. While prescriptive analytics methods have been frequently applied to optimize demand management decisions on the operational and tactical level, model-based approaches for strategic service design are scarce to date. In this talk, we present new ideas on how to apply prescriptive analytics to strategic demand management in order to profitably capture the demand potential for attended home delivery services.

3 - Integrated Demand Management and Vehicle Routing for Shared Mobility-on-Demand Systems in Rural Areas
Fabian Anzenhofer, David Fleckenstein, Robert Klein, Claudius Steinhardt

The steadily growing number of shared mobility-on-demand services bears the potential to make public transport more customer-friendly, sustainable, and profitable by pooling customers with compatible itineraries. At present, the growth of such services is primarily limited to cities. However, in rural areas, providers struggle to operate profitably as demand is lower and more dispersed, making efficient pooling of different customer requests challenging. We consider a rural service provider that dynamically receives a stream of customer requests via a mobile application and must control both the booking process and service fulfillment. From the operational planning perspective, this leads to an integrated demand management and vehicle routing problem with overlapping booking and service horizons, which we formalize as a Markov decision process. Tractable solution concepts usually rely on decomposition, i.e., they determine demand control and vehicle routing decisions based on a feasibility check and an opportunity cost estimation for each arriving customer. We present such a decomposition-based solution concept specifically adapted to the problem setting of service providers in rural areas. Drawing on a data-driven case study, we investigate in which environments active demand management can contribute to the system performance.

4 - Pricing Optimization in Combined Car Sharing Car Rental Systems
Matthias Soppert, Ralph Angeles, Beatriz Brito Oliveira, Claudius Steinhardt

Increasing fleet utilization is one of the main drivers to improve the operational performance in car sharing as well as in car rental. This is why most recently, traditional car rental companies have begun to additionally offer car sharing products, and vice-versa. We study the control of a combined car sharing car rental system by means of temporal price differentiation with the objective to maximize profits. Both products, i.e. short-term rentals of the car sharing product and long-term rentals of the car rental product, address different customer segments with different demand patterns, price sensitivities, etc.. However, both products use the same resource, namely the same vehicle fleet. Short-term rentals which typically last several minutes have a higher profit per minute than the long-term rentals which typically last several days. Since the absolute profit of a single long-term rental can only be egalized by several short-term rentals, the operator of the combined car sharing car rental system needs to determine how to allocate the resources best in this network setting - indirectly through pricing.

Wednesday, 13:00-14:30

■ WC-04

Wednesday, 13:00-14:30 - 10.11 Hertz-Hörsaal

Semi-infinite Optimization

Stream: Continuous and Global Optimization
Invited session
Chair: *Oliver Stein*

1 - Lipschitz and Hölder stability of solution sets to perturbed optimization problems
Diethard Klatte

In this talk, we study finite-dimensional minimization problems under small data perturbations. We will present conditions for calmness or Hölder calmness of the optimal solution set mapping, which is a property guaranteeing a Lipschitz or Hölder type estimate of perturbed solutions to the minimizing set of some initial problem. Starting with conditions for an abstract parametric optimization problem, we will specialize them to particular settings including standard nonlinear programs and convex semi-infinite problems. By our approach, we refine well-known results from the classical optimization literature in the 1980s and 1990s. For more details, we refer to the paper by D. Klatte and B. Kummer, "On Hölder calmness of minimizing sets", Optimization, published online April 2021.

2 - A tri-level approach for T-criterion-based model discrimination
Jan Schwientek, David Mogalle, Philipp Seufert, Karl-Heinz Küfer, Michael Bortz

When modeling real processes, often several different models fit. For being able to distinguish (discriminate) which model is best suited, one is interested in so-called T-optimal designs. These consist of the points which maximize the deviation between the models, under the condition that the models are fitted best on those points to each other. From an optimization point of view, the T-criterion constitutes an infinite-dimensional min-max (bi-level) optimization problem. In the inner optimization, one minimizes the error integral with respect to the parameters, whereas the outer optimization consists of finding a probability measure on the design space maximizing the same integral. For the solution of this problem, dedicated descent methods have been developed, firstly. Those are very robust, but only converge slowly. In recent years, techniques from semi-infinite optimization have been applied either linearizing the inner parameter estimation problem or refining a discretization of the parameter space. While the former approach leads to performant, but unreliable algorithms, the latter requires the solution of the estimation problem to global optimality which is time-consuming. If one decouples the design weights from the design points in the semi-infinite formulation, one ends up in a tri-level optimization problem. To solve this formulation of the T-criterion, we propose an algorithm which alternately refines discretization of the parameter as well as of the design space. In comparison to other semi-infinite approaches, we obtain inner problems which are well suited concerning global optimization. We prove convergence of our method and show on the basis of discrimination tasks from chemical engineering that our approach is stable and outperforms the known methods.

3 - Optimality and duality for approximate solutions in nonsmooth semi-infinite optimization programs involving approximate pseudoconvexity
Tamanna Yadav, S. K. Gupta

We consider a class of semi-infinite optimization models with cone constraints. Firstly, a necessary optimality condition for quasi−solution of the optimization model is developed using Abdaie constraint qualification. Then, the concept of quasiconvexity over cones is introduced and a sufficient optimality condition is proposed using approximate pseudoconvexity and quasiconvexity assumptions. Further, Mond-Weir dual is presented and weak, strong and converse duality results between the semi-infinite optimization model and the dual problem are proved under approximate pseudoconvexity and quasiconvexity assumptions. Also, We derive the weak, strong and converse duality results between the semi-infinite optimization model and corresponding Wolfe type dual problem under the assumptions of approximate pseudoconvexity and quasiconvexity. Moreover, to justify the main results, numerical illustrations have been shown at suitable places.

4 - Semi-infinite models for equilibrium selection
Oliver Stein, Maren Beck

In their seminal work 'A General Theory of Equilibrium Selection in Games' (The MIT Press, 1988) Harsanyi and Selten introduce the notion of payoff dominance to explain how players select some solution of a Nash equilibrium problem from a set of nonunique equilibria. We formulate this concept for generalized Nash equilibrium problems, relax payoff dominance to the more widely applicable requirement of payoff nondominatedness, and show how different characterizations of generalized Nash equilibria yield different semi-infinite optimization problems for the computation of payoff nondominated equilibria. Since all these problems violate a standard constraint qualification, we also formulate regularized versions of the optimization problems. Under additional assumptions we state a nonlinear cutting algorithm and provide numerical results for a multi-agent portfolio optimization problem.

■ WC-05

Wednesday, 13:00-14:30 - 11.10 Engelbert-Arnold-Hörsaal (EAS)

Lot Sizing and Scheduling

Stream: Supply Chain Management
Invited session
Chair: *Thomas Volling*

1 - The Lot Size Adaptation Approach for the Two-Level Stochastic Capacitated Lot-Sizing Problem
Markus Mickein, Knut Haase

We propose a Two-Level Stochastic Capacitated Lot-Sizing Problem (2L-SCLSP) under random demand and service level constraints. We apply the static and static-dynamic uncertainty strategy for the finished products. While the static strategy determines robust production plans, the static-dynamic strategy allows adjustments of lot sizes depending on demand realizations. However, flexible production plans by the static-dynamic strategy affect upstream processes within a multilevel production system. Mainly, the production and storage capacity limitations, holding costs, lead times, and shelf life of semifinished goods restrict the application of the static-dynamic strategy. This study presents a novel model formulation for the 2L-SCLSP of the lot size adaptation approach. Several scenarios within a scenario sample model the demand uncertainty. The scenario samples are generated by a multi-period descriptive sampling method. To solve the 2L-SCLSP, we apply a general solution approach for scenario-approximated problems. We evaluate 729 test instances to quantify the performance of the uncertainty strategies depending on several impact factors. The results show that the performance depends on the cost ratio between the finished and semifinished goods. The computational study demonstrates the importance of considering upstream processes when applying the static-dynamic uncertainty strategy.

2 - A hybrid algorithm for a job shop scheduling problem with machine- and sequencing-flexibility
Lars Müller, Simon Komesker, Julia Rieck

The trend towards product diversification and individualization resulted in considering alternative concepts to enable flexible and adaptable production systems. We consider a modularly structured manufacturing process found, e.g., as a concept in the automotive industry. In this environment, schedules for jobs have to be created according to a job shop scheduling problem. However, restrictions regarding the flexible structure have to be taken into account. On the one hand, alternative machines can be selected for processing individual operations of a job. Furthermore, the precedence relationships between the operations of a job are not necessarily linear, but can be given by a directed, acyclic precedence graph. On the other hand, certain operations of a job can be executed in parallel with other operations; in contrast to the classical job shop scheduling problem. Thus, the resulting optimization problem corresponds to a job shop scheduling problem with machine and sequencing flexibility. The problem is formulated by a mixed-integer linear model with the objective of minimizing the total cycle time (makespan). Moreover, other relevant problem aspects, such as transportation and setup times as well as release dates of machines, are considered. A hybrid solution method based on the metaheuristics tabu search and variable neighborhood search is adapted and further developed. Additional measures for intensification and diversification within the approach are used selectively. Extensive analyses

are performed to investigate the efficient use of the solution procedure in terms of solution quality and solution time.

3 - A matheuristic for scheduling parallel heterogenous continuous steel annealing lines

Sebastian Wegel, Anton Ivanov, Ralf Lenz, Thomas Volling

Continuous annealing is a typical process in steel cold-rolling facilities, where long steel strips, wound up to coils, are processed through an annealing furnace in a continuous strip to achieve defined material properties. To enable a continuous process, the coils are welded together before entering the line and are separated again afterwards. Coil specific characteristics, such as width, thickness and annealing temperature impose restrictions on the compatibility of two consecutive coils. Whenever such incompatibility occurs, the coils must be bridged with a special dummy coil called stringer. We consider parallel heterogenous lines for this process, where coils can only be processed on certain lines according to their width. The problem is to simultaneously assign coils to lines and sequence them on these lines, while minimizing the number of stringers needed and the total tardiness of all coils. We formulate the problem as a mixed-integer linear problem (MILP), based on a model developed by Mujawar et al (2012). To solve the problem, we propose a two-phase heuristic with an opening and an improvement phase. In the opening phase, a greedy heuristic is used to generate an initial solution in a very short time. To further improve that solution, we develope a tailored matheuristic based on Fix-and-Optimize that applies problem specific decompositions. Preliminary results for instances with up to 300 coils show that the developed two-phase heuristic outperforms a commercial state-of-the-art solver, both in the quality of solutions and computation time. It therefore offers promising potential for use within an industrial context.

■ WC-06

Wednesday, 13:00-14:30 - 10.91 Redtenbacher-Hörsaal

Multi-Criteria Optimisation and Assessment of Energy Systems

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

1 - Life cycle-based environmental impacts of energy system transformation strategies for Germany: Are climate and environmental protection conflicting goals?

Tobias Naegler, Jens Buchgeister, Heidi Hottenroth, Sonja Simon, Ingela Tietze, Tobias Viere, Tobias Junne

In the development of climate-friendly energy system transformation strategies it is often ignored that environmental protection encompasses more than climate protection alone. Consequently, an assessment of environmental impacts of energy system transformation strategies is required if undesired environmental side effects of the energy system transformation are to be avoided and transformation strategies are to be developed that are both climate and environmentally friendly. For this presentation, ten structurally different transformation strategies for the German energy system were re-modelled (in a harmonized manner). Life cycle-based environmental impacts of the scenarios were assessed by coupling the scenario results with data from a life cycle inventory database focusing on energy and transport technologies. The results show that the transformation to a climate-friendly energy system reduces environmental impacts in many impact categories. However, exceptions occur with respect to the consumption of mineral resources, land use and certain human health indicators. The comparison of environmental impacts of moderately ambitious strategies (80% CO2 reduction) with very ambitious strategies (95% CO2 reduction) shows that there is a risk of increasing environmental impacts with increasing climate protection, although very ambitious strategies do not necessarily come along with higher environmental impacts than moderately ambitious strategies. A reduction of environmental impacts could be achieved by a moderate and - as far as possible - direct electrification of heat and transport, a balanced technology mix for electricity generation, by reducing the number and size of passenger cars and by reducing the environmental impacts from vehicle construction.

2 - A multi-perspective approach for exploring the scenario space of future power systems

Karl-Kiên Cao, Ulrich Frey, Thomas Breuer, Manuel Wetzel, Shima Sasanpour, Kai von Krbek

There are many possible future energy system pathways, many of them unforeseen. We explored the range of conceivable parameter values starting with an extensive literature review. Based on this, experts quantified parameter interrelations to generate multiple scenarios ensuring only sensible parameters combinations remained as inputs to an energy system optimization and coupled models. In the past, computational limitations have been a major obstacle to span such an enormous space of scenarios. Therefore, we used the high-performance computer (HPC) JUWELS. To utilize this HPC system efficiently, the parallel solver for linear programs, called PIPS-IPM++, has been further developed. We integrated this solver into a tool chain of different components including scenario generation, energy system optimization and results evaluation and met the challenge of coupling a large diversity of software packages in a fully automated workflow. Implementing this HPC workflow enabled us to calculate all scenarios in a matter of days. Finally, we compiled a set of more than 40 indicators to provide comprehensive assessments of simulated energy systems. Thus, we covered multiple evaluation perspectives, such as system adequacy, security of supply or economic performance. First results for 1000 simplified optimization models of Germany proof the plausibility of our approach. As next step, we will investigate both spatially highly resolved energy systems and Unit Commitment models with discrete investment decisions. With our final results we expect to pave the way to more robust energy system modeling. This enables the derivation of measures for achieving least cost and fully-decarbonized energy supply or for preparing for disruptive events like price shocks in the vast parameter space

3 - Multi-Objective Investment Optimization of Energy Systems for Residential Quarters Considering Costs and Life-cycle Environmental Impacts

Heidi Hottenroth, Ingela Tietze, Tobias Viere

The decision on which energy system to prefer is mostly based on cost and climate indicators. However, this falls short when it comes to preventing burden shifting to other environmental concerns when transforming to renewable energy: e.g. the installation of renewable electricity generators in many cases leads to a high demand for mineral and metals. Such shortcomings can be overcome by combining energy system modelling (ESM) and life cycle assessment (LCA) in a multi-objective optimization. The target function of the developed LCA-based energy decision support tool LAEND accounts for energy systems' environmental footprint (16 impact categories) and costs simultaneously. LAEND follows a multi-period myopic optimization approach and is applicable on the level of residential quarters. The resulting investment and dispatch planning of renewable energy systems takes into account sector-coupling through combined heat and power, electric mobility, heat pumps, and electric heating units. Further possible technologies are wind power, photovoltaics, solar collectors, wood furnaces, batteries, and thermal storages. In a first case study, LAEND is applied to a newly built residential neighborhood with five multiple dwellings in an urban area in southern Germany. The results show different system configurations depending on the optimization goal and the assigned weights, which tend to higher installed capacity with lower climate impact and therefore relatively high costs. The multi-criteria optimization, which combines environmental and cost criteria, reveals those system configurations that compensate best for the different objectives. Further model developments are planned to take into account energy efficiency measures and changing parameters over time.

4 - A highly adaptable multi-objective energy system optimisation framework - implementation and case studies

Jonas Finke, Valentin Bertsch

Energy systems affect people's lives in many ways. These impacts and thus people's interests in energy systems are as diverse as the systems themselves. However, many energy system models (ESMs), as a major tool for supporting decisions in the sector, focus on cost optimisations and are designed for application to a rather specific group of energy systems. In order to address the lack of highly adaptable ESMs with multiple objectives, we present an implementation of the augmented epsilon-constraint method with the open-source energy system optimisation framework Backbone. It enables the optimisation of a broad range of energy systems with respect to various objectives. Further analyses of the resulting set of Pareto-optimal solutions allow to

improve decision support in different applications. To highlight the adaptability of the implemented method, we present a number of case studies ranging from residential to international scale, across the electricity and heat sector and objectives such as costs, environmental impacts and self-sufficiency.

■ WC-07

Wednesday, 13:00-14:30 - 10.91 Grashof-Hörsaal

Individual Decision Making and Experimental Behaviour

Stream: Decision Analysis and Support
Invited session
Chair: *Heike Schenk-Mathes*

1 - Advice Discounting: The Role of Advisors' Financial Incentives

Robert Gillenkirch

This study investigates the role of financial incentives provided to an advisor in a judge-advisor-system, where a judge makes an initial judgment, receives information from an advisor and then makes a final judgment. Prior research has identified various determinants of advice discounting, which is the under-utilization of advice by the judge. Results from two experiments identify the financial incentive provided to the advisor as a determinant of advice discounting. Implementing different tasks, the experiments manipulate the advisor's pay to be either fixed or performance-based, and, nested in the performance-based pay condition, the performance measure to be either individual performance (the accuracy of the advice given) or group performance (the accuracy of the judge's final judgment). Results indicate that a financial incentive for providing accurate advice does not affect advice discounting relative to a fixed payment, whereas judges give significantly more weight to advice in their final estimations, and make predictions that are significantly closer to the advice they receive, when the advisors' pay is based on group performance. We provide evidence for judges' cooperativeness perceptions mediating the relationship between the advisor's financial incentive and advice discounting, but find no evidence supporting the view that judges' beliefs in the effects of financial incentives drive the results.

2 - Do non-linear utility functions matter? A practical analysis of the impact of non-linear utility functions on the final ranking of alternatives

Mendy Tönsfeuerborn, Rüdiger von Nitzsch, Johannes Siebert

Multi-attribute utility theory is broadly used to evaluate alternatives. Decision makers can express their preferences using partial utility functions. The simplest shape of a utility function is linear. However, a variety of other, more complicated shapes exists. Following the assumption that the more precisely the preferences are modeled, the better the results of the decision analysis are, researchers have developed sophisticated methods to elicit preferences as precisely as possible. These time intensive methods lead often to non-linear utility functions. We found only scarce empirical evidence analyzing to what degree the precise elicitation of preferences is worth the effort. We investigate the extent to which linearization of non-linear utility functions leads to rank shifts, especially of the best-ranked alternative. We analyzed more than 1,000 decisions in the decision support tool Entscheidungsnavi. The participants were trained in using the Entscheidungsnavi and spent several hours with their decision. Therefore, we assume that they articulated their preferences accordingly. Most participants used non-linear utility functions. We calculated the rankings for the participants' stated preferences when all utility functions were linearized. Our analysis reveals that in approximately 90% of cases, linearization of utility functions did not affect the best-ranked alternative. We provide recommendation when to use on non-linear utility functions.

3 - Changes in Value Priorities due to the COVID-19 Pandemic - A 3-year longitudinal study with german students.

Christian Hannes, Rüdiger von Nitzsch

In March 2020, the WHO declared the corona disease (COVID-19) a pandemic. Since then, the German government has tried to control the spread of the virus with various restrictions. These restrictions had a direct impact on the life of German citizens. Young people and students were also affected. Previous studies have shown that extreme events (e.g. Sortheix et al. (2019), Verkasalo et al. (2001)) directly impact personal value priorities. In this study, we investigate to which extent the COVID-19 pandemic and its restrictions lead to a change of value priorities of German students. We conducted a longitudinal study from January 2020 to January 2022 with three measurement points and 968 participants. One measurement point is shortly before the first outbreak of the COVID-19 in Germany, one directly after the second lockdown period and the third after two years after the beginning of the pandemic. In this study, the students were asked to indicate their value priorities while solving a real-world decision problem important to them. Results indicate short-time changes in value priorities in accordance with Maslow's theory of motivations. Values and needs that are under fulfilled become more important, and those over fulfilled lose priority. Only the value priority of self-direction show an significant (t = 0,001, Cohen's d = 0,204) increase that could be long-term.

4 - Social Identity and Status: Experimental Evidence on the Interaction of In-Group Bias and Status Differences in Natural Groups

Janina Kraus

Starting with Akerlof and Kranton (2000) there is a rapidly growing literature on social identity in economics. Many experiments show that social identity affects individual behavior and leads to in-group favoritism. According to social identity theory, individuals prefer groups/individuals with a higher status as comparisons with other groups are more beneficial (Tajfel, Billig, et al. 1971; Tajfel 1972, 1978; Tajfel and Turner 1979). In the economics literature, only a few papers deal with how in-group bias varies with the status of individuals or groups (see. e.g., Paetzel and Sausgruber 2018; Hett et al. 2020) Even if status and identity are prominent topics in psychology and economics, the interaction of identity and status is still not fully understood. Therefore, this study tries to contribute to and extend the existing findings.

This study presents findings from a unique data set of German soldiers who differ with respect to (i) their military unit (airforce, navy and army) and their (ii) status as being officer (high status) and recruit for becoming officer (non-commissioned officers). This natural occurring setting allows us to check whether in-groups bias between groups (horizontal level) vary with differences in status (vertical level). Using a series of modified dictator games and a questionnaire, we find that identification of soldiers as being a soldier is strong (26% more transfers to soldiers). Identification between units is the same for all units and is surprisingly high. We also find that horizontal identification interacts with status. On the vertical dimension, we do not find a differentiation between status groups for transfer behavior of officers.

■ WC-08

Wednesday, 13:00-14:30 - 10.50 HS 102

Power Systems Planning and Optimization II

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Anil Kaya*

1 - An Optimization Model for Production Scheduling with Energy Consumption and Energy-related Emissions

Hajo Terbrack, Thorsten Claus, Frank Herrmann

Due to the scarcity of resources, rising costs as well as the further need for ecological improvement in industrial production, firms are increasingly motivated to take into account energy consumption in production planning. Associated with this, the consideration of energy-related emissions is becoming an additional point of interest for decision-makers in both, economic and ecological terms. Based on an extensive systematic literature review, the study at hand presents a multi-criterial scheduling problem that addresses tardiness, energy consumption and energy-related emissions in production scheduling. A MILP

model is introduced that takes into account job release dates, multiple machine states, a power demand threshold as well as time-varying emission conversion factors. Multiple case studies are analysed and the effects of different technological implementations as energy onsite generation and energy storage systems are evaluated. Furthermore, several price mechanisms regarding energy procurement and emission trading are discussed. Moreover, by coupling the optimization model to a discrete event simulation model, we are able to compare the model results to real case scenarios. First computational experiments have demonstrated that the model and its extensions can effectively reduce the environmental impact associated with production while simultaneously considering corresponding economic objectives. Based on the proposed approach, our research aims on answering the question with which economic trade-offs an ecological improvement in terms of energy consumption and emission output can be achieved in production.

2 - Intersecting near-optimal feasible spaces: robust energy system designs over multiple decades of weather data
Koen van Greevenbroek, Aleksander Grochowicz

We suggest a new methodology for designing robust energy systems. For this, we investigate so-called near-optimal solutions to energy system optimisation models; solutions whose objective values deviate only marginally from the optimum. Using a refined method for obtaining explicit geometrical descriptions of these near-optimal feasible spaces, we find designs that are as robust as possible to perturbations. This contributes to the ongoing debate on how to work with and define robustness in energy systems optimisation. We apply our methods in an investigation using multiple decades of weather data. For the first time, we run a model of the European power system with a high temporal resolution over 41 years of weather data. While an optimisation over 41 years is at the limits of computational feasibility, we use the near-optimal feasible spaces over single years to gain an understanding of the design space over the full time period. Specifically, we intersect all the near-optimal feasible spaces for the individual years in order to get designs that are likely to be feasible over the full time period. We indeed compute such designs and verify their feasibility by simulating the resulting system operations over four decades. Our work builds on recent developments in the field, using techniques like Modelling to generate alternatives (MGA) and Modelling all alternatives (MAA), and provides new insights into the geometry of near-optimal feasible spaces and the importance of multi-decade weather variability for energy systems design. We also provide an effective way of working with a multi-decade time frame in a highly parallelised manner. Our implementation is open-source, easy to use, and is based on PyPSA-Eur.

3 - Parallelization of energy system optimization models using modified dual decomposition
Stefan Strömer

Linear programming (LP) is utilized by many energy system tools to optimize large scale models, but suffers from stagnating sequential computing power, further aggravated by continuously rising model size and complexity. Various approaches from optimization theory, like delayed column generation, exist to tackle the challenge of transforming given problems, in order to utilize parallel computing to solve models (faster). Of those, decomposition methods have been studied thoroughly for decades in operations research and energy related research, but are not commonly implemented in many energy system models.

We consider a decomposition approach commonly referred to as dual decomposition using Lagrangian relaxation. Related to energy systems, it allows a direct explainability of separating (sub-)problems using shadow prices (e.g. in the form of electricity prices when using a spatial decomposition of regions). However, this advantage comes with a major downfall that prevents it from being applied in an automated fashion to arbitrary models: The inherent stepwise behaviour of many components (e.g. merit order based market clearing) significantly hampers the convergence of the iterative algorithm.

To counteract this effect, we utilize domain knowledge from energy systems to modify the basic algorithm. Artificially constraining the decomposed variables improves the algorithm's convergence, while conclusions from LP sensitivity analysis improve the iterative choice of shadow prices. We implement an open-source algorithm, apply it to relevant examples and solve the resulting LPs. Based on the results, we compare the performance of the now easily parallelizable algorithm with an unmodified decomposition approach as well as with solving the full model in a single pass.

4 - Network Design Problem for Biogas Plants
Arne Heinold, Daniel Schröer, Lisa Herlicka, Frank Meisel, Uwe Latacz-Lohmann

In this talk, we consider the design of a pipeline network for biogas plants in Germany. The problem has synergies with a minimal spanning tree problem but plants do not have to participate in the network and sub-networks are possible (e.g., it might be optimal to build several smaller networks instead of one large network). We use a real-world setting in which we consider non-linear investment and operating costs for edges and nodes. We model the problem as a mixed-integer linear program and solve it via CPLEX with the objective of maximizing total profits. Due to the size and complexity of the problem, we use a decomposition in which we pre-assign plants to sub-networks and solve each problem separately. Our results show that profitable pipeline networks are possible and, with this, they support a possible business plan for biogas plants in the light of expiring governmental funding.

■ WC-09

Wednesday, 13:00-14:30 - 10.50 Raum 604

Local energy markets and energy communities

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Hannes Hobbie*

1 - Towards decentralized Models for day-ahead scheduling of energy resources in Renewable Energy Communities
Louise Sadoine, Martin Hupez, Zacharie De Greve, Thomas Brihaye

Renewable energy communities (RECs) are one of the driving factors for ensuring the energy transition. These consist in decentralized market mechanisms enabling local electricity exchanges among end-users, and bypass the traditional wholesale/retail market structure. In this configuration, local consumers and prosumers (i.e. consumers who also produce electricity) join together in collectives, known as communities. They can either cooperate or compete to achieve a (possibly common) goal, which may be economic, environmental, or social. We address electricity consumption scheduling on a day-ahead basis within a community of prosumers that own renewable generation. To this end, we mobilize prosumer flexibility to optimize energy exchanges based on the desired objective (e.g. the electricity bill). First, we establish a typology of community market designs that enable virtuous coordination between members. Among them, we design different centralized and decentralized schemes. In the former, a centralized planner globally optimizes the common objective, while in the latter, each member optimizes its consumption based on its energy preferences. We, therefore, place particular emphasis on modeling strategic behavior. The natural interdependence between members sharing a common network, reflected by an aggregate network tariff component, leads to the formulation of non-cooperative games. In addition, excess rooftop solar power production can be valued inside or outside the community. We analyze the existence, uniqueness, and computation of Nash equilibria. We use distributed algorithms that ensure confidentiality and do not require third-party intervention. For all different models, we evaluate the efficiency of the results and provide insight into their respective incentives

2 - Market equilibria on regional flexibility markets for congestion management considering a strategic aggregator
Hannes Hobbie, Matthew Schmidt, Ramteen Sioshansi, Dominik Möst

Future decentralised energy systems require novel solutions for managing congestions in power grids. These also entail new forms of coordination between grid operators and flexibility suppliers. End-users typically own the needed flexible applications, e.g. heat-pump, electric vehicles, but have limited access to wholesale markets. Potential solutions must involve them to exploit needed flexibility potentials. In this context, regional flexibility markets and aggregators who manage the bundled energy procurement will likely play an essential role in the market-based coordination of flexibility provision between grid operators and end-users.

Besides technical challenges, aspects related to market design issues and individual stakeholders' preferences substantially impact possible design solutions. Whereas operators seek to implement congestion

management measures according to the regulatory framework, end-users and regional aggregators usually endeavour to maximise their own utility or profits.

In order to consider these aspects in a modelling framework, the application of bi-level programming and complementarity systems is proposed to investigate potential design solutions for regional flexibility markets. Expected findings of this work particularly will highlight how strategically behaving aggregators may impact equilibria on regional flexibility markets and how different market design options may prevent resulting market inefficiencies.

■ WC-10

Wednesday, 13:00-14:30 - 20.30 SR 0.014

Production and distribution problems

Stream: Logistics
Invited session
Chair: *Steffen Rudert*

1 - Different MIP Formulations for a Dynamiclot-sizing Model with Rework of Defectives

Steffen Rudert

This paper discusses a general dynamic lot-sizing model with rework of defectives. Due to the imperfect production process, some fraction of the generated items is not of sufficient quality. After rework, these goods serve the same demand as the initial perfect quality items; both are called serviceables. Production and rework are conducted independently from another at different or same periods. The general model is proven to be NP-hard. We present three main unique characteristics that describe the specific model behavior observed in optimal solutions: production only, multiple rework, and overproduction of serviceables. To analyze the effects of these three unique characteristics on the optimal solutions, different MIP formulations are derived that exclude each of these unique characteristics from the general model. Afterward, computations for given data sets are conducted, using all different MIP formulations. It can be shown that production only occurs most frequently and has the highest effect on the total cost.

2 - An Evaluation of Several Routing and Storage Policies for the Single Picker Routing Problem with Scattered Storage

Laura Korbacher, Katrin Heßler, Stefan Irnich

The process of collecting items of a customer's order from different storage locations in a warehouse accounts for the lion's share of the operating costs of the warehouse. Hence, optimizing the picker's route is an important instrument to reduce costs. We examine the single picker routing problem (SPRP) with scattered storage (or mixed shelves) in a one-block warehouse. While in classic storage each stock-keeping unit is assigned to one picking position in the warehouse, in scattered storage a stock-keeping unit is distributed to several picking positions throughout the warehouse. Based on an extension of the state space of Ratliff and Rosenthal's dynamic program, we propose a network flow model consisting of a shortest path problem with additional covering constraints. In addition to exact routing, the generic approach can be employed to the established routing heuristics traversal, return, largest-gap, midpoint, and composite by mild adaptions in the state space. Extensive experiments highlight a cost comparison of the different heuristics among each other for scattered storage warehouses. In addition, we investigate whether the observations on the cost difference between heuristic routing tours for different location assignments can be transferred from classical SPRP to SPRP with scattered storage.

3 - An Extended Model Formulation for the Two-Dimensional Irregular Strip Packing Problem Considering General Industry-Relevant Aspects

Hédi Király, Alf Kimms

Two-dimensional cutting and packing problems with irregular objects (nesting problems) deal with the positioning of irregular as well as regular shaped objects without overlapping inside the boundaries of one or more pieces of raw material whether regular or irregular in shape. Our focus is on the irregular strip packing problem, where a finite number of rotations of convex as well as non-convex polygons with and without holes are permitted. The objective is to minimize the needed length of the rectangular raw material with a fixed width. To deal with the geometry of irregular objects, direct trigonometry is applied. In addition to the general requirements, aspects and characteristics that are typical for many affected industries are also taken into account. Objects are often created by assembling smaller sub-elements using a variety of techniques, such as welding metal plates, gluing wooden panels, or sewing garments. Also, whether the raw material is single-colored or has a particular structure or pattern is of great importance. In the latter case, special attention must be paid to the rotation of certain sub-elements and objects to achieve the desired (uniform or non-uniform) appearance of the final product. To address the mentioned aspects, a mixed-integer linear model is introduced, which is an extension of a formulation published by previous authors. Furthermore, the method of calculating "critical vertices" is presented, which requires only a reduced number of comparisons between edges and vertices of two objects to ensure overlap-free positioning.

4 - Considering Correlation in Customer's Orders in the Balancing of Assembly Lines

Celso Gustavo Stall Sikora

Modern assembly lines must be amenable to the production of multiple products requiring little or no setup. Due to the numerous configurations and add-ons, a customer can select for a product, the combination of all options results in an astronomical number of possible products. In the automotive industry, some manufacturers often report over a trillion of possible vehicle combinations. Under such high product variety, it is difficult to design an assembly line by considering (or optimizing) the production sequence.

This work extends an algorithm presented previously for the balancing of assembly lines under a random sequence of products. The products are defined as a combination of the ordered options and an algorithm based on a Branch-and-Bound algorithm is proposed to explore all possible assembly line configurations. In each node, the expected utility work is calculated using a Markov Chain.

The extension presented here deals with correlations between the tasks' options. These correlations can represent add-ons that are often purchased together and can greatly affect the assembly time of the vehicles. A dataset is generated and tested by assigning correlations randomly between pairs of options. Surprisingly, the solution method provides, on average, cheaper line configurations under correlated options compared to the independent probabilities.

■ WC-11

Wednesday, 13:00-14:30 - 10.50 Raum 602

Renewables and energy efficiency

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Marianna Russo*

1 - Short-term Risk Management of Electricity Retailers Under Rising Shares of Decentralized Solar Generation

Marianna Russo, Emil Kraft, Valentin Bertsch, Dogan Keles

Electricity retailers face increasing uncertainty due to the ongoing expansion and self-consumption of unpredictable distributed generation in the residential sector. We analyze how increasing levels of households' solar PV self-generation affect the short-term decision-making and associated risk exposure of electricity retailers in the German day-ahead and intraday markets. First, we develop a stochastic model accounting for correlations between solar load, residual load and price in sequentially nested wholesale spot markets across seasons and type of day. Second, we develop a computationally tractable two-stage stochastic mixed-integer optimization model to investigate the trading portfolio and risk optimization problem faced by retailers. Through conditional value-at-risk we assess the retailers' profitability and risk exposure to different levels of PV self-generation by assuming different retail tariff schemes. We find risk-hedging trading strategies and tariffs to have greater impact in Summer and with low levels of residual load in the system, i.e. when the solar generation uncertainty affects more the households' demand to be served and the wholesale spot prices. The study is innovative in unveiling the potential of dynamic electricity tariffs, which are indexed to spot prices, to sustain

a high penetration of renewable energy source while promoting a fair risk sharing between retailers, regular consumers and prosumers (consumers with self-generation). Our findings have implications for electricity retailers facing load and revenue risks in wholesale spot markets, likewise for regulators and policy-makers interested in electricity market design.

2 - Optimal policy instruments for residential self-consumption: A deep reinforcement learning driven policy design
Mohamed Saâd El Harrab, Michel Nakhla

Self-consumption is a regulatory framework intended to promote local consumption over export. With the rapid emergence of Prosumers, this new mode of consumption will improve the profitability of renewable energy sources produced by grid-connected residential systems (Nano Grids) and reduce the stress on the electricity distribution grid due to the fluctuating and the intermittent nature of wind and solar energy sources.

In order to maximize residential self-consumption, optimal policy instruments need to be designed. Theoretical approaches and empirical studies are limited and fail to capture the complexity of the real world and the behavioral responses to policy instruments.

Deep Reinforcement Learning and Optimization techniques for policy design show promise towards overcoming existing limitations. The challenge with policy design comes from needing to solve a highly non-stationary and sequential decision-making problem where all actors (the agents and the regulator) are learning: economic agents learn rational, utility-maximizing behaviors and the regulator learns to optimize its own objective via optimal policy choices.

This work presents a novel Deep Reinforcement Learning approach to design and validate effective policy instruments to promote self-consumption. We analyze the impact of different policy instruments on the behavior of the Prosumer agent.

3 - Bi-objective optimization of renewable fuel supply chains regarding total costs and land-use
Mina Farajiamiri, Grit Walther

The production of alternative fuels using renewable resources like biomass, CO2, and electricity from solar and wind power is a promising way to reduce GHG emissions in the transportation sector in all applications that can not be electrified (e.g., long-haul trucks, aviation, marine). However, besides the challenges that arise from the seasonal availability of these resources, there is also intense competition for these limited renewable resources, and the land that is available to grow biomass or install PV and wind power plants is limited. Against this background, we propose a long-term horizon multi-stage supply chain model for alternative fuels considering the seasonality of resources, herein applying a bi-objective formulation that minimizes the total cost of the system and direct land-use simultaneously. An augmented epsilon constraint method is used to address the trade-off between these two objective functions. Based on the trade-off between cost and land-use, different strategies can be derived for network design, including different production pathways, resource utilization, and land allocation.

4 - Maximization of the Smart Readiness Indicator of Buildings under Budget Constraints
Tristan Emich, Shiva Faeghinezhad, Kunibert Lennerts

The smart readiness indicator (SRI) is a method proposed by the European Commission which calls for better use of the potential of smart technologies in the building sector. The introduction of the SRI is intended to raise awareness of smart building technologies and make the added value more available for building users, owners, and providers of smart services.

With the SRI assessment method, the technological smart readiness of buildings can be determined. The method has 54 questions, which are divided into nine domains, such as heating, domestic hot water, cooling, ventilation, lighting, electricity, electric vehicles, dynamic envelope and monitoring & control. Each question of which is assessed with up to five different levels representing incremental levels of technological equipment. These questions form the basis for the calculation of the SRI score.

Improving the SRI score of a building, it is a challenging task to choose the technologies which bring the maximum SRI score improvement using a limited budget. Therefore, the aim of this paper is to help the decision makers to come up with the correct choices that have the highest impact on the SRI score. The chosen solution method here is a problem specific non-dominated sorting genetic algorithm (NSGA). The proposed method is then applied to a set of hypothetical buildings to demonstrate its applicability and capability.

■ WC-12

Wednesday, 13:00-14:30 - 10.50 Raum 701.3

(e-)Mobility services

Stream: Mobility and Traffic
Invited session
Chair: *Melanie Reuter-Oppermann*

1 - Passengers and Drivers have their Meeting Points in Method
Nitin Ahuja

The last decade has seen an unprecedented rise of ridesharing (resp. ride-hailing) services. Two of their big promises are convenience and serving more demand with roughly the same number of vehicles. Lately, to deliver on their second promise, some services have started asking their passengers to walk to or from a location. For example, a passenger might want to walk for five minutes to an agreed upon meeting point for pickup. By doing this, vehicle-tours tend to become more efficient and passengers save money.

Using meeting points in a dynamic ridesharing system is an algorithmic as well as a computational challenge. On the one hand, a ridesharing query with meeting points should be answered roughly as quickly as a query without them. On the other hand, meeting points should yield sensible vehicle-tours leading to better resource utilization and system efficiency.

In this talk we present our approach that addresses, among other issues, the challenges mentioned above. It is assumed that meeting points are given as input. We also present some computational results underlining the effectiveness of our approach.

2 - Simulation-Optimisation for Optimal Location of Wireless Charging Infrastructure for an Electric Taxi Fleet
Andrea Raith, Anton Aish, Grant Covic, Patrick Jochem, Melanie Reuter-Oppermann, Jade Xiao

Electric vehicles (EVs) are playing a major role in the decarbonisation of transport systems, especially in countries where electricity can be generated sustainably. Commercial vehicle fleets such as taxis are often early adopters of efficient and cost-effective vehicle technologies such as EVs. However, taxi drivers may have concerns due to limited battery range, limited availability of charging locations, inability to operate while charging, as well as having to reject passengers due to insufficient battery state-of-charge (SOC). Some of these concerns could be overcome by convenient wireless charging infrastructure that is placed at taxi ranks where taxis can charge while they wait in the queue. We describe the development of a simulation of a taxi service that operates either exclusively with EV taxis, or a mixed fleet of taxis. This simulation enables us to capture how an electric taxi service could operate in the future, and will help better design and locate charging infrastructure. Our simulation captures battery SOC during taxi operations and charging, and is able to consider plug-in and wireless charging. A local search heuristic is developed that identifies good locations of charging stations, and the number and type of chargers needed. The simulation is implemented in Julia using the SimJulia package. We will present a case study to demonstrate the simulation-optimisation approach for charger locations of an EV taxi service, and will discuss our findings with particular focus on performance of the system with plug-in or wireless charging options.

3 - The HARMONY Strategic Simulator: large-scale digital modelling to inform policy and decision making
Fulvio Lopane

HARMONY is a project under the CIVITAS Initiative, an EU-funded programme whose aim is to provide metropolitan authorities with a multiscale spatial and transport planning framework to foster a sustainable transition towards a low-carbon new mobility era. HARMONY's main objective is to assist metropolitan authorities with evidence-based decision making, by providing a state-of-the-art model suite that quantifies the multidimensional impact of various policies, investments, and mobility concept applications. To achieve this goal, the HARMONY model suite is structured on three different levels: 1) Strategic (long-term) demographic land-use transport models, 2) Tactical (mid-term)

people and freight activity-based models and 3) Operational (short-term) multimodal network models. This talk is dedicated to the Strategic level, whose outcome is the Strategic Simulator, which captures long-term decisions and emerging patterns in terms of population distribution, job market, land uses, economic sectors, infrastructure development and travel and activity demand. The main components of the strategic simulator are a demographic forecasting model, a regional economy model, a land-use transport-interaction model, a land development model, a spatial-interaction freight model, a synthetic population model and a long-term households and individual choice model. The structure of the framework is modular and allows the employment of all or only a selection of components: according to data availability and the scope of the analysed case study, different models can be selected and different scenarios can be set up to produce a wide portfolio of results and outputs to evaluate the impacts of developments, interventions or policies and to inform strategic decision making.

4 - Towards the use of e-ambulances in the German emergency medical services system
Melanie Reuter-Oppermann

Using electric vehicles as private cars as well as for public transport is an important step towards the reduction of CO2-emissions and hopefully slowing down climate change. In Germany, emergency medical services transport thousands of patients each day. Electrifying ambulances could therefore make a significant contribution. In case of emergency rescues, ambulances must be available immediately. Therefore, practitioners are doubting whether currently existing vehicles offer a sufficient range. In contrast, time uncritical patient transports are often known in advance and might therefore be scheduled in such a way to allow the use of e-ambulances, potentially as part of a mixed fleet. We use the transport data from a German coordination centre to analyse the number and distribution of patient transports that could have been performed by an e-ambulance and determine locations for potential charging stations. In addition, we discuss the potential of applying optimisation approaches to schedule patient transports in order to increase the use of a-ambulances.

■ WC-13

Wednesday, 13:00-14:30 - 20.30 SR -1.025

Parallel Solvers

Stream: Software Applications and Modeling Systems
Invited session
Chair: *Yuji Shinano*

1 - The UG framework version 1.0: An update
Yuji Shinano

The Ubiquity Generator Framework (UG) version 1.0 was released last year. It was designed to parallelize powerful state-of-the-art branch-and-bound based solvers externally in order to exploit their powerful performance. We call the underlying solvers "base solvers"; originally, a base solver is a branch-and-bound based solver, but in the current release, it is redefined as any solver that is being parallelized by UG, since, in version 1.0, it was generalized to be a software framework for high-level task parallelization. In this talk, we present the concept of high-level task parallelization and its flexibility. We will show a few recent success stories of the instantiated parallel solvers by UG version 1.0.

2 - A parallel algorithm combining relaxation and heuristic for the integrated long-haul and local vehicle routing problem on an adaptive transportation network
Junko Hosoda, Stephen Maher, Yuji Shinano, Jonas Christoffer Villumsen

Consolidation of commodities and coordination of vehicle routes are fundamental features of supply chain management problems. Supply chain management problems integrating the designation of consolidation locations with the coordination of long haul and local vehicle routing is a complicated problem. An algorithm combining relaxation and heuristic is proposed to find high quality solutions. The relaxation solver bounds the solution space taking into account the tendency of solution space and heuristic solver founds the high quality solution in the bounded solution space that satisfies all constraints. The UG framework is used to parallel execution of relaxation and heuristic solvers. The results demonstrate impact of parallel execution of relaxation and heuristic on the execution time for the integrated long-haul and local vehicle routing problem on an adaptive transportation network.

3 - Solve Large Scale Open QAPs by Massively Parallel DNN-based Branch-and-bound MethodWe report our progress on the project for solving large scale quadratic assignment prob
Koichi Fujii

We report our progress on the project for solving large scale quadratic assignment problems (QAPs).

Our main approach to solve QAPs is a parallel branch-and-bound method efficiently implemented on a powerful computer system, using the Ubiquity Generator Framework (UG) which can utilize more than 100,000 cores.

Though the Lagrangian doubly nonnegative (DNN) relaxation of QAPs generate less nodes than other lower bound procedures, it requires much more computational time to solve one node. Since solving QAPs is different from solving MIP by LP-based branch-and-bound at this point, we added some new features to UG.

The checkpointing mechanism is implemented in UG to save nodes in branch-and-bound tree for the calculation of the supercomputers with limited available time. Usually UG avoid to collect all the open nodes in branch-and-bound tree at generating checkpoint file. The new feature Enhanced Checkpoint is added to UG to collect all the open nodes at the end of the execution. This helps a lot to avoid calculating redundant nodes in multiple execution. The new feature Huge Checkpoint File Split is also added to UG to deal with huge number of nodes in checkpoint files by split nodes into two groups.

In this talk, we describe the details of new features of UG for solving QAPs and present some preliminary numerical results of solving large QAPs including open QAPLIB instance tho40, which we solved for the first time.

4 - Faster solution of sparse MaxCut and QUBO problems
Daniel Rehfeldt

The maximum-cut problem is one of the fundamental problems in combinatorial optimization. With the advent of quantum computers, both the maximum-cut and the equivalent quadratic unconstrained binary optimization problem have experienced much interest in recent years.

This talk introduces a new solver to find optimal solutions to both of these problems. The main focus lies on sparse problem instances, although also dense ones can be solved. We enhance several algorithmic components such as reduction techniques and cutting-plane separation algorithms, and combine them in an exact branch-and-cut solver. Furthermore, we provide a parallel implementation. The new solver is shown to significantly outperform existing state-of-the-art software (including Gurobi) for sparse and even various dense MaxCut and QUBO instances. Furthermore, we improve the best-known bounds for several instances from the 7th DIMACS Challenge and the QPLIB, and solve some of them (for the first time) to optimality.

■ WC-14

Wednesday, 13:00-14:30 - 10.50 Raum 702

Carsharing

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

1 - Matching versus individual choice: How to counter regional imbalance of carsharing demand
Rea Röntgen, Dirk Briskorn, Nils Boysen, Michael Dienstknecht

Free-floating car sharing offers its users the possibility to return a rented car at any location (i.e. not necessarily at the original starting location) in a predefined service area. This regularly leads to an imbalance between available cars and customer demand in the service area, i.e., cars are left in areas of low demand while customers in areas of high demand face a shortage of cars. This problem is exacerbated when demand fluctuates over time. For this reason, one of

the main problems of free-floating sharing systems is to maintain the service area cost-efficiently balanced. To address this, we introduce a new approach based on a reservation-based sharing system where cars are assigned to customers instead of being selected by the customers themselves, which is the case in the status quo. The resulting problem to match sharing provider's car supply and the user's car demand can be seen as a minimum cost flow problem which can be solved in polynomial time, and therefore is suitable for real-time application. In this talk we present the results of a comprehensive computational study, in which we compare our approach with the status quo in two different test environments: an artificially generated dataset and a real dataset from a car sharing system in Munich, Germany.

2 - A Branch-and-Cut algorithm for the autonomous dial-a-ride problem with incompatible customer types
Arne Schulz, Christian Pfeiffer

In this talk, we consider a dial-ride problem with autonomous vehicles. We focus on the aspect that customers might feel unsafe in a driverless vehicle if they are alone with customers of a certain type. Therefore, we allow customers to exclude customer types from a shared ride with them. These incompatible customers are not allowed to be in the vehicle at the same time. We present a Branch-and-Cut algorithm as well as computational experiments for the problem setting.

3 - A general framework to evaluate different rebalancing operation strategies in one-way car sharing systems
Selin Ataç, Nikola Obrenović, Michel Bierlaire

Car sharing (CS) services have become popular due to their financial and environmental benefits. The CS operators have offered flexibility by allowing one-way trips which resulted in vehicle imbalance in the service area. They have then introduced rebalancing operations to reduce the imbalance thus, to increase the level of service. The methods studied in the literature focus on forecasting the demand to determine the rebalancing strategy. This work proposes a framework which compares different strategies to solve rebalancing operations in one-way station-based car sharing systems in terms of cost and level of service. Since it is exhausting to collect the data to develop a demand model, we feed the trip demand output of Multi-Agent Transport Simulation Toolkit (MATSim) as an input to our framework. This also allows us to explore the different uncertainties that can occur in the system, such as fluctuations in trip demand. The results of the framework help the decision maker to better analyze the system and choose the best rebalancing policy under different scenarios.

4 - User-based redistribution of free-floating carsharing system through user coproduction
Mireia Roca-Riu, Christoph Heitz

Free-floating carsharing systems are operated in different regions as the most flexible version of carsharing. Users book a vehicle standing near the origin of their trip and then drop the vehicle somewhere within the service region. Users use an app to find and book the vehicles and trips are usually charged by the minute. The operation of such services has been a challenge for multiple operators world-wide. One of the challenges is that demand is usually not symmetric, then the operator needs to regularly relocate vehicles, which usually entails very high costs. The redefinition of such a service where users become coproducers is a promising solution to improve the performance. Users become coproducers as they help to bring vehicles to places where they will be used. Through an intelligent incentive system, incentives are be offered for users to pick up vehicles standing at unattractive locations or offered to users which drop-off vehicles in regions where there are no vehicles available. The potential of such a system is investigated together with a free-floating carsharing operator. This is part of a project where empirical social research and operations research are brought together to develop a system that considers the specifics of the service region and its customers preferences. In this work, we present a simulation tool that allows us to obtain insights on the effect of such incentives in the system. The simulation uses an origin/destination demand model to locate the start and end of the trips. Users are assumed to react to incentives by walking further to pickup/dropoff if incentives are offered, but also performing additional trips. The total number of trips, and the costs of incentives given are used as indicators of the performance of the system.

■ WC-15

Wednesday, 13:00-14:30 - 10.50 HS 101

Discrete Optimization Problems II

Stream: Discrete and Combinatorial Optimization
Invited session

Chair: *Imke Joormann*

1 - Vehicle Routing with Heterogeneous Time Windows
Tim Niemann, Petra Mutzel, Lukas Schürmann, Sebastian Stiller, Andreas M. Tillmann

We consider a novel variant of the heterogeneous vehicle routing problem (VRP) in which each customer has different availability time windows for every vehicle. In the literature, heterogeneous VRPs typically assume differences in properties of the vehicle fleet such as costs or capacities, but time windows of customers appear to have been regarded only in a homogeneous fashion. The motivation of our model comes from a real-world practical application that seeks to plan a delivery schedule for one vehicle and a fixed set of customers whose availability times differ from day to day; each day, the vehicle travels a different route such that at the end of a given time horizon, all customers have been visited. In particular, the approach also allows for customers to be completely unavailable for arbitrary time spans.

To solve the problem, we propose a branch-and-price framework based on a set partitioning formulation together with a problem-specific labeling algorithm and bespoke heuristics. By branching on the time windows, we can utilize the heterogeneous structure to reduce the depth of the branching tree. Analyzing the pricing problems separately for different days allows us to reduce the subproblem sizes significantly compared to the homogeneous case by only considering subgraphs induced by customers with a time window on the respective day. Furthermore, we can use parallelization to speed up computations.

In a numerical evaluation, we demonstrate that our special branching rule performs better than the common arcflow branching and that the running time of our algorithm depends strongly on the number of time windows per customer.

2 - Aircraft fleet planning: An optimization approach integrating CO_2 trading systems
Lisa-Marie Manke, Imke Joormann

The aviation sector is responsible for at least 2.5% of the worldwide emitted CO_2 emissions today and the pressure on airlines to reduce the emitted emissions is continuously increasing. Due to new fuel-efficient air frame and engine technologies, aircraft modernization offers an opportunity to reduce annual emissions. But with limited production capacities of the manufacturers and related costs, it is not possible to renew a whole fleet at once. At the same time, CO_2 trading systems lead to higher costs for older fleets. Therefore, there needs to be long term planning regarding the fleet composition of an airline. For this, the fleet planning problem determines economically optimal replacement times for aircraft. The fleet planning problem can be formulated as a MILP and combines fleet composition and fleet assignment. The fleet composition problem considers different aircraft types as well as retrofits; here, retrofits are modifications of aircraft to lower the amount of emitted emissions without replacing the whole aircraft. These aircraft are then used within the fleet assignment problem to fulfill a given demand of flights. With this, it is possible to compute the emitted CO_2 emissions for the next period. The emissions are then considered within CO_2 trading systems as that is currently the only affecting restriction for airlines concerning CO_2 emissions. Modeling the trading systems, the emissions get divided between ones emitted on an international flight and the ones emitted on an inter-European flight, as there are vast differences between both trading systems.

3 - Separating setup and quantity decisions in stochastic lot sizing models
Manuel Schlenkrich, Sophie Parragh

When dealing with optimization problems that include uncertain input parameters, two popular modelling approaches are available in the literature. Stochastic programming approximates the distribution of the uncertain parameters by discrete scenarios aiming at minimizing the expected costs over these scenarios. Robust optimization serves as a worst-case approach hedging solutions against unfavorable realizations of the stochastic parameters. We investigate two-stage stochastic programming and robust optimization for multi-item multi-stage capacitated lot sizing under demand uncertainty. The objective is to minimize the overall costs consisting of production-, setup-, holding- and backlog costs. For the stochastic model the flow of information needs to be specified by deciding on which variables are fixed before

the uncertain parameters are realized and which can still be adapted afterwards. In the context of lot sizing usually setup and production quantity decisions are fixed, while inventory and backlog variables act as the recourse variables. We investigate the case of only fixing setup decisions in the first stage, while shifting quantity decisions to the second stage, representing a more flexible approach of planning. For the stochastic programming approach this formulation leads to significantly larger and therefore more complex models. Since solving the compact model of this formulation is already challenging for small instances we tailored a Benders decomposition approach to the problem. We compare this formulation to the stochastic version where setup and quantity decisions are made in the first stage, as well as to a static budget-uncertainty robust approach. We analyze the obtained production plans and investigate the impact of being more flexible in planning.

■ WC-16

Wednesday, 13:00-14:30 - 20.30 SR -1.012

Optimal Control Theory and Applications

Stream: Continuous and Global Optimization
Invited session
Chair: *Andrea Seidl*

1 - On Uniqueness of Linear Markov Perfect Equilibria in Linear-Quadratic Differential Games: A Geometric Approach

Markus Eigruber, Franz Wirl

Even tough the possibility of multiple nonlinear equilibria in linear-quadratic differential games is extensively discussed, the literature on models with multiple linear Markov perfect equilibria (LMPEs) is scarce. And indeed, almost all papers confined to a single state (a very large majority of the application of differential games to economic problems) identify a unique LMPE. This paper explains the finding of uniqueness and derives conditions for multiplicity. The conditions are derived from a joint analysis of the phase plane in the state and the derivative of the value function and the respective auxiliary system. In addition, and in contrast to the purely arithmetic examples from the literature and own examples, we provide an economic (IO, learning by doing) setting, where multiple LMPEs naturally arise.

2 - A Theory of Quality Time: The Seneca Model

Andreas Novak, Joao Ricardo Faria

This paper adapts Seneca's ideas on time in the Ramsey model. Considering quality time as a state variable yields the optimal use of real time, which depends positively on the utility parameter of quality time and negatively on the initial level of quality time, impatience, marginal learning cost of philosophy and time variation of quality time. With non-separable preferences between quality time and consumption, the optimal use of time also depends positively on consumption. In this case, unlike the Ramsey model, the modified golden rule does not apply. Optimal consumption and capital stock are determined simultaneously with quality time, and philosophizing may affect economic growth in contraposition to Seneca's thought.

3 - The optimal momentum of population growth and decline

Gustav Feichtinger, Stefan Wrzaczek

Some fifty years ago, Nathan Keyfitz (1971) asked for the amount a growing human population would further increase if its fertility rate would be reduced immediately to replacement level and remains there forever. The reason for this demographic momentum is an inertia of age structures containing relatively many potential parents due to past high fertility. Although nobody expects such a miraculous reduction of reproductive behavior, a gradual decline of fertility in fastly growing populations seems inevitable.

Since any delay in fertility decline to a stationary level leads to an increase of the momentum, it make sense to think about the timing and the quantum of the reduction in reproduction. More specifically, we consider an intertemporal trade-off between costly family planning measures and the demographic momentum at the end of the planning period. Using the McKendrick partial differential equation for the age-structured population dynamics, the present paper studies this problem in a distributed parameter control framework. An appropriate extension of Pontrayagin's maximum principle allows us to the derive interesting insights into the qualitative structure of the optimal path of fertility control and the resulting salvage momentum. A peculiar property of these age-structured models is the occurence of the reproductive value as part of the shadow price. Finally, let us stress the fact that our model can also be applied in a symmetric way to determine efficient pro-natalistic measures for shrinking populations, a situation prevailing now in several developed countries.

4 - On the occurrence of abnormal thresholds in optimal control problems

Andrea Seidl, Gustav Feichtinger, Dieter Grass, Richard Hartl, Peter Kort

In many interesting economic applications of optimal control multiple optimal solutions can occur. In the present talk we take a closer look at so-called Stalling equilibria which serve as threshold between two different long run outcomes. The key feature of a Stalling equilibrium is that it is impossible to increase the state value beyond this point which is due to the state dynamics usually in combination with a control constraint. In the present talk, we will discuss how different parameter values lead to the occurrence of threshold points, indifference points and Stalling equilibria in context of an optimal control problem. We derive conditions for the occurrence of abnormal solutions in an advertising diffusion problem and discuss their economic implications.

■ WC-17

Wednesday, 13:00-14:30 - 20.30 SR -1.011

Transportation and Routing

Stream: Health Care Management
Invited session
Chair: *Teresa Melo*

1 - Simulation-optimisation framework for analysing patient transport planning in case of mass casualty incidents

Florentina Hager, Melanie Reuter-Oppermann

In case of a mass casualty incident, a high number of patients needs to be triaged, receive first care on the scene and potentially be transported to a hospital. The "SimPaTrans" project funded by the German Federal Office of Civil Protection and Disaster Assistance aims to build a simulation-optimisation framework for the analysis of patient transport logistics in the case of a mass casualty incident taking the expected outcome of different patient groups into account when allocating resources. In the SimPaTrans tool, multi-criteria optimisation approaches are combined with agent-based simulation models. These make suggestions for the assignment of vehicles to patients and patients to hospitals, as well as determine suitable locations for different transport vehicles types like trains or buses with the aim of reaching patients as quickly as possible when needed. In addition to the development of a generic disruption scenario framework, the framework also enables the adjustment of different risk-relevant parameters. The simulation tool will support the strategic decision making as well as the design of operational plans. In this talk, we will present and discuss first models and approaches as well as different potential use cases in Germany.

2 - Consistent nurse-patient assignment for home healthcare services with nurse absences

Bruno Albert Neumann Saavedra, Marlin Wolf Ulmer

Home healthcare services (HHS) medically assist patients at their residences. To this end, nurses of an HHS sequentially visit and service patients over the day, e.g., routing of ambulances is determined. In particular, a patient is assigned to a nurse who regularly serves her. Such a consistent nurse-patient assignment makes medical service more comfortable and efficient since nurses learn about the need of patients through regular interactions with them. Nevertheless, nurses have a relatively high absence rate because of sickness. If a nurse is sick, the patients must be reassigned to another nurse or even outsourced e.g., to another HHS, if there are not enough nurses available to serve all patients. In this talk, we investigate the problem of determining consistent nurse-patient assignments to minimize the number of reassignments and outsourced services in the case of nurse absences. To

do so, we introduce a two-stage stochastic program, in which the absence of nurses on representative days is depicted by scenarios. To solve real-world-sized instances, we propose a column-generation-based matheuristic. The matheuristic carefully fixes decisions related to the assignment and routing decisions and solves the resulting restrictive model with a solver. We provide evidence about the efficacy of the solution approach in an extensive computational study.

3 - Less is more: A simulation-based inferential statistical analysis of subsequent steps in triage algorithms

Melina Ruf, Jens Brunner, Christina Bartenschlager

The number of terrorist attacks per year increased by approximately 25% worldwide from 2018 to 2020. Since such an attack usually injures many people in a geographically limited space within a very short time, this is referred to as a mass casualty incident (MCI). As soon as such an MCI occurs, injured patients are to be prioritized based on their urgency of treatment for the definition of a treatment sequence. For this purpose, special triage algorithms exist. The algorithms query certain characteristics of the patients in subsequent steps. Based on the presence or absence of these characteristics, patients are assigned to predefined triage categories determining the treatment priority. In the context of an MCI, time is an important parameter, as not all patients can be treated simultaneously due to staff and capacity restrictions. Therefore, a simulation-based inferential statistical analysis is applied to research whether existing algorithms can be terminated prematurely without a significant decrease in the quality of the results, i.e., sensitivity, specificity, and Area under the Curve (AUC). By early termination time could be saved during triaging, which in turn secures an earlier start of the treatment and might contribute to an optimal medical outcome.

■ WC-18

Wednesday, 13:00-14:30 - 20.30 SR -1.013

Planning service delivery

Stream: Logistics
Invited session
Chair: *Stefan Pilot*

1 - Service Network Design for Next-day Mail Delivery

Stefan Pilot, Julian Rothermel, Michael Schneider

Our industry partner Deutsche Post DHL Group (DPDHL) aims to render its next-day mail delivery operations more efficient by optimizing its long-haul transportation network. This network is used to transport mail trays produced at origin sorting centers to their destination sorting centers for processing. DPDHL's objective is to minimize transportation cost while still delivering as many letters as possible on the next business day. Planners face the following trade-off: on the one hand, mail trays must be consolidated to reduce transportation costs; on the other hand, consolidation is time-consuming, and little time is available because of the commitment to next-day delivery and slow processing at the destination sorting centers. We formalize the planning of the long-haul mail transportation as a service network design problem. We use a time-expanded graph to model flows of mail trays, vehicles, and other transportation equipment through space and time. Our model takes into account complex constraints imposed by the layout of DPDHL's logistics facilities and their operational practices. To solve large real-world instances, we develop a heuristic solver, and we explain how the model and heuristic are used to provide DPDHL with decision support for tactical and strategic planning tasks.

2 - Collaborative Transportation Planning for Attended Home Deliveries

Margaretha Gansterer, Steffen Elting, Jan Fabian Ehmke

This presentation focuses on the opportunities of horizontal carrier collaboration for Attended Home Deliveries (AHD). Before vehicles start their route, customers dynamically request a delivery from one of the carriers in the collaboration network. Upon request disclosure, the carrier offers a set of delivery time windows to the customer. Once a time window has been agreed upon, the order cannot be canceled in favor of another order that is requested later. After the order arrival phase, an auction-based framework permits collaborating carriers to buy and sell delivery requests without disclosing business information. Every carrier submits a fraction of its accepted requests to a shared auction pool. A limited number of attractive request bundles are centrally assembled from that pool, and all participating carriers submit their corresponding marginal delivery cost as the bid price for each of these bundles. The solution to the Winner Determination Problem determines the new allocation of orders to carriers. We quantify the collaboration gain of this network by solving the underlying problems for dynamic customer acceptance, vehicle routing, and the combinatorial auction. We investigate the general impact of delivery time windows on network-wide travel durations. We will tailor specific parts of the auction mechanism to include time window information and deploy strategic procedures of dynamic customer acceptance to study the potential of request exchanges for AHD.

3 - A Heuristic Solution Framework for Field Service Planning with Time-dependent Travel Times

Fabian Meyer, Katharina Glock, Daniela Grimm, Frank Radaschewski, Jakob Wagenblatt

The field service planning problem seeks to plan daily tours for service technicians, i.e., skilled workers who install technical equipment and fulfil maintenance tasks. Tasks have time windows indicating when a client is available and may require certain skills that must be possessed by the assigned technicians. Furthermore, tasks may require multiple technicians for example due to their difficulty (e.g., handling) or because the necessary skills cannot be fulfilled by a single employee. Since traffic conditions vary over time (e.g., rush hours) travel times between task locations are time-dependent. While some of these tasks are scheduled several weeks in advance, others arise in the short term. These are, for example, emergency maintenance tasks in case of failures, or follow-up appointments if a task cannot be completed as planned due to time constraints. As these short-term tasks constitute a significant proportion of the overall workload, it is possible that there are more tasks than could be reasonably completed. In this case, it is necessary to select tasks that can be completed while delaying others. To this end, tasks can be associated with priorities, e.g., based on the criticality of a failure or the contractual agreements with a customer. In this talk, we propose a heuristic solution method developed together with PTV Group for planning operative tours for several technicians. We model the problem as a team orienteering problem with time windows, dynamic team building and time-dependent travel times and introduce an adaptive large neighbourhood search procedure to determine solutions within reasonable time. First results based on a real-world case study demonstrate the applicability of the approach.

4 - Discrete-Time Performance Analysis of Stochastic Order Fulfilment Systems with Cutoff Service Levels

Uta Mohring, Christoph Jacobi, Kai Furmans

Providing flexible and reliable customer-oriented service has become a crucial competitive requirement in order fulfilment. Concurrently, customer demand is highly volatile and order fulfilment systems operate against fixed deadlines, e.g. truck departures. To ensure high customer satisfaction in this challenging environment, operations managers usually establish service promises including specific predefined cutoff times: Orders arriving until the cutoff time are promised to be completed by the upcoming deadline, whereas orders arriving after the cutoff time are completed by the subsequent deadline. Cutoff service levels measure to which extent these service promises are met. In our work, we introduce a discrete-time Markov chain for exact performance analysis of stochastic order fulfilment systems with cutoff service levels. The model incorporates a time-dependent general distributed discrete order income and a general distributed discrete processing performance. It enables the exact calculation of two types of cutoff service levels: alpha- and beta-service level. Numerical analysis indicates that there is a trade-off between flexibility and reliability requirements of service promises in order fulfilment: Operations managers can guarantee either high flexibility, that is, a cutoff time shortly before the deadline, or high reliability, that is, a service level close to 100%. However, they can systematically affect this trade-off by taking efforts to decrease system utilisation and variability of processing performance of the order fulfilment system.

■ WC-19

Wednesday, 13:00-14:30 - 20.30 SR 0.019

Integrating Machine Learning and Optimization

Stream: Analytics and Learning
Invited session
Chair: *Kevin Tierney*

1 - Real-Time Multiserver System with Single Joint Queue Ample Repair Teams and Preemptive Priorities Working in General Regime

Joseph Kreimer

We consider a real-time data acquisition and processing multiserver and multichannel system with identical servers (such as unmanned air vehicles, machine controllers, medical monitoring devices, overhearing devices, etc.) which can be maintained/programmed for different kinds of activities (e.g. passive or active). This system provides a service for real-time jobs arriving via several channels (such as surveillance regions, assembly lines, communication channels, etc.) and involves maintenance. We focus on the system working in general regime with preemptive priorities assigned for servers of different activity types. We consider the model with ample repair teams and single joint queue to all channels. We focus on real time systems (RTS) with a zero deadline for the beginning of job processing. Queueing of jobs in such systems is impossible, since jobs are executed immediately upon arrival, conditional on system availability. That part of the job which is not executed immediately is lost forever and cannot be completed later. Each server can serve different channels, but not simultaneously. There is exactly one job in each channel at any moment (there are no additional job arrivals to busy channels), and therefore one server at most is used (with others being in maintenance or on stand-by or providing the service to another channel) to execute the job in this channel at any given time. Different parts of the same job can be executed by different servers. Servers are identical, but may be maintained/programmed for different types of activities. We show how to compute steady state probabilities and various performance measures, when both operation and maintenance times as well as jobs interarrival and duration times are exponentially distributed.

2 - Artificial Intelligence for Managing Operational Capacities: A Deep Demand Response Program

Gunther Gust, Marie-Louise Arlt, Dirk Neumann

Renewable energies require new approaches to the operation of power systems. In this work, we present a novel Demand Response (DR) program based on Deep Reinforcement Learning for electricity procurement on energy markets. The program stands out by adjusting electricity prices online and solely based on observed aggregate electricity consumption. It thereby avoids privacy concerns and expensive information system infrastructure investments. Additionally, it can cope with non-elastic and time-interdependent demand—which is typical for storage devices and industrial processes. Specifically, we model four flexible load types and provide a unified framework of load modeling under uncertainty and with time- interdependencies. Numerical experiments show that our DR program achieves considerable and stable welfare benefits in comparison to conventional DR programs. Moreover, the solution approach based on Deep Reinforcement Learning reaches these savings after a short learning periods corresponding to only few simulation days. Regarding load flexibility, we find that the responses of the four load types strongly differ depending on prices and the lag between the announcement and the application of price changes ('notification interval') which is an important design parameter. Our results imply that system operators should flexibilize their DR programs with the help of learning algorithms and tailor their program to the local load composition and forecasting quality. For researchers, our solution approach can help to solve pricing problems with unknown and heterogeneous demand, which occurs on online platforms and in other environments.

3 - Learning to Solve a Stochastic Orienteering Problem with Time Windows

Kevin Tierney, Fynn Schmitt-Ulms, André Hottung, Meinolf Sellmann

Reinforcement learning (RL) has seen increasing success at solving a variety of combinatorial optimization problems. These techniques have generally been applied to deterministic optimization problems with few side constraints, such as the traveling salesperson problem (TSP) or capacitated vehicle routing problem (CVRP). With this in mind, the recent IJCAI AI for TSP competition challenged participants to apply RL to a difficult routing problem involving optimization under uncertainty and time windows. We present the winning submission to the challenge, which uses the policy optimization with multiple optima (POMO) approach combined with efficient active search and Monte Carlo roll-outs. We present experimental results showing that our proposed approach outperforms the second place approach by 1.7%. Furthermore, our computational results suggest that solving more realistic routing problems may not be as difficult as previously thought.

■ WC-20

Wednesday, 13:00-14:30 - 20.30 SR 0.016

Procurement Auction Design

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

1 - Optimism and Pessimism in Auctions

Tobias Riehm

In auctions bidders are usually assumed to have rational expectations with regards to their winning probability. However, experimental and empirical evidence suggests that agents can manipulate their expectations if that leads to higher utility, resulting in optimism or pessimism. Optimism increases ex ante savoring, while pessimism leads to less dis- appointment ex post. Hence optimal expectations depend on the time left until the uncertainty is resolved, i.e. the time one can savor ex ante by being (too) optimistic. Applying the decision theory model of Gollier and Muermann (2010) on First Price Auctions, I show that by decreasing the time between bids and revelation of results, the auctioneer can induce bidders to forego optimism, leading to more aggressive bids and thereby higher revenues for the auctioneer. Finally I test these predictions experimentally.

2 - Commitment in first-price auctions

Jeff Starck

Consider a standard first-price procurement auction in which the buyer lacks the commitment not to renegotiate with the winning bidder upon conclusion of the auction. The theoretical prediction for such a setting is stark: equilibrium bids are uninformative; the buyer selects a winning bidder and makes them an optimal take-it-or-leave-it offer, leading to a higher expected price than in a setting with commitment. We take this prediction to the laboratory. While we find that bidders bid significantly higher in the no-commitment setting vis-à-vis the setting with commitment, prices are not significantly different across the treatments. This moderates the theoretical prediction, suggesting that, at least in some settings, a lack of commitment need not negatively influence the price resulting from an auction.

3 - Dutch vs. First-Price Auctions with Expectations-Based Loss-Averse Bidders

Jonas von Wangenheim

We study Dutch and first-price auctions with expectations-based loss-aversebidders and show that the strategic equivalence between these formats no longer holds. Intuitively, as the Dutch auction unfolds, a bidder becomes more optimistic about her chances of winning; this stronger attachment effect pushes her to bid more aggressively than in the first-price auction. Thus, Dutch auctions raise more revenue than first-price ones. Indeed, the Dutch auction raises the most revenue among standard auction formats. Our results imply that dynamic mechanisms that make bidders more optimistic raise more revenue, thereby rationalizing the use of descending-price mechanisms by sellers in the field.

4 - Quality Requests in Procurement Auctions

Lijia Tan

In real-world procurement, verifying the qualities provided by suppliers before the transaction is very costly for buyers in many circumstances. Sending suppliers messages requesting a specific quality can be a cost-effective way to increase the supplied quality in procurement, especially when the quality is hard to verify upfront. We incorporate sellers' guilty aversion in a buyer-determined auction, demonstrating the impact of the quality request on supplied quality analytically. Next,

we use a laboratory experiment to examine how sellers react to buyers' quality requests in our controlled environment. In the experiment, we consider two types of quality requests - non-binding and binding requests, corresponding to CC and IC treatments respectively. We observe that sellers positively react to the non-binding requests. We also observe that buyers do not ask for maximum quality when the requests are binding. Furthermore, we testify whether sellers' guilty aversion can be enhanced if buyers forgo a binding request. In the new B75 and B90 treatments, buyers get to choose either a low efficient binding request or a non-binding request before an auction starts. We find that such forgoing effort made by the buyer does not influence sellers' guilty aversion much. As a result, we conclude that a non-binding request is effective to increase the supplied quality if making a binding request is not realistic. However, forgoing inefficient binding requests harms buyers' surplus because that does not help to achieve a sufficiently high supplied quality level.

■ WC-21

Wednesday, 13:00-14:30 - 30.96 Seminarraum 1. OG (R104)

Scheduling applications

Stream: Project Management and Scheduling
Invited session
Chair: *Simone Neumann*

1 - A heuristic bicriteria scheduling approach for flooring production planning

Dominik Leib, Elisabeth Finhold, Till Heller

We consider a scheduling problem motivated by a particular process step in the production of rubber flooring. In this step, a set of given production orders of different materials and colors has to pass through a single heated pressure roller which can process one order at a time. Since different materials require different process temperatures and heating up and cooling down the machine requires a significant amount of time (or, equivalently, costs), we want to minimize the total heating/cooling time. On the other hand, we aim for smooth color transitions to minimize cleaning effort and the risk of contamination. Therefore, our goal is to find production sequences which are Pareto optimal. We model the problem as a special case of a bicriteria traveling salesperson problem and provide an heuristic algorithm which does a problem-driven breadth-first search to compute elements of the Pareto front of the set of materials with regard to both criteria. The algorithm keeps track of representatives for a certain set of values of one criterion which are then optimized with respect to the other criterion in each iteration step, where each optimization step is done in a way respecting the one dimensional nature of the objectives.

2 - Scheduling Unrelated Parallel Machines with Attribute-Dependent Setup Times: a Case Study

Sven Jäger, Neele Leithäuser, Sebastian Velten, Christian Weiß

In this talk we study a practical scheduling problem which arises in many production processes. It can be viewed as an unrelated parallel machine scheduling problem with deadlines and sequence-dependent setup times.

Importantly, the setup times are not arbitrary but dependent on certain job attributes, such as material, color or size of the final product. A setup is necessary whenever there is a value change in at least one attribute between a job and its direct successor on the same machine. Each attribute has a fixed setup time associated with it, independent of the exact values the attribute takes for the specific predecessor and successor jobs. This means, for example, that a change in color always takes a fixed number of hours, independent of the exact predecessor and successor color.

The goal is to complete all jobs on time, and to minimize both the total setup time and the number of setups made. Minimizing the total setup time means that more time can be spent on actual production. This allows for additional jobs to be scheduled or the available jobs to more reliably be scheduled within their deadlines. Minimizing the number of setups made is desirable, since stopping and restarting machines for a setup can increase the risk of breakdowns and quality problems. Thus, it is preferable to let a machine run the same product for as long as possible, even if setup times may be small.

We study an instance provided by an industrial partner and use a constraint programming approach to reduce setup times and number of setups made when compared to the real data. In addition, we consider several heuristic algorithms and compare them to our constraint program.

3 - Interval scheduling with resource availability and adjacency constraints

Michael Dienstknecht, Dirk Briskorn

In our research, we consider matching supply and demand in the context of a large-scale construction project. More specifically, we focus on the on-site accommodation of the workforce - a complex planning task for the rental companies providing the accommodation facilities (mostly containers). Usually, the single trades being involved in the project share information regarding their demand, i.e. the period of time in which they are active and the required number of each type of container (e.g. office, rest room, sanitary), with the rental company. The rental company then is responsible for providing the respective containers and assigning the trades to them. The containers are usually arranged in a so-called container unit, i.e. a designated area on the construction site where containers are grouped next to and stacked on top of each other. Due to efficiency considerations it is desirable to not disperse trades all over the unit, but to build trade clusters instead, i.e. to assign the same trade to clusters of adjacent containers. These assignments may have to be revised over time due to the dynamic nature of the project. However, causing overhead for the trades and fines for the rental company, re-assignments must be held to an absolute minimum. We address the problem faced by the rental company: assigning trades to containers such that re-assignments are minimized while accounting for different container types, limited container availability times and the clustering of trades. We provide different MIP formulations for the problem and, as we find standard solver CPLEX struggling with larger instances, employ a fix-and-optimize heuristic for solving the problem.

4 - Optimizing storage and retrieval in fully automated grid-based storage systems

Simone Neumann, Nicolas Fauvé, Florian Jaehn

In the fast-growing online market, e-grocery providers in particular advertise fast delivery times. These can only be achieved through flexible and compact warehouse solutions close to the customer. Furthermore, in-store compact storage solutions can offer added value as a complementary element in brick and mortar stores. Compactness usually goes hand in hand with poor accessibility and thus higher access times. In a dense storage system, storage units (SKUs) are stacked on top of each other and also next to each other, which prevents direct access. To address this weakness, we propose a new theoretical solution for compact storage. A temporary aisle is created to access a specific SKU within a densely packed storage grid. An autonomous shuttle enters this aisle via a lift and retrieves the SKUs. As long as this aisle exists, no temporary aisle can be created in the neighborhood, blocking access to other SKUs. In this talk, we give a detailed problem description and derive a static 2D subproblem. The subproblem is examined for its cost structure and properties.

Wednesday, 15:00-16:00

■ WD-02

Wednesday, 15:00-16:00 - 30.95 Audimax A

Semi-plenary talk Eichfelder

Stream: PC Stream
Semi-plenary session
Chair: *Oliver Stein*

1 - Algorithmic developments in multiobjective optimization
Gabriele Eichfelder

In multiobjective optimization one considers optimization problems with several competing objective functions. Such problems arise in a large variety of applications. They play, for instance, an important role in models of the energy market when intelligent neighborhood networks have to be integrated in overarching distributing networks and a variety of individual and competing criteria have to be taken into account. Next to multiple objective functions, these problems often possess additional difficulties as discrete-continuous variables, bilevel structures, or uncertainties.

In this talk we give an introduction to multiobjective optimization. We shortly present the most widespread solution approach which is known under the name scalarization. There, one formulates parameter-dependent single-objective replacement problems and solves those iteratively for a set of parameters. We discuss the limits of such approaches in terms of quality guarantees and for specific classes of optimization problems as those with additional difficulties as mentioned above. Moreover, we give some of the basic ideas of direct methods which avoid to scalarize first and, thereby, try to overcome some of these issues.

■ WD-03

Wednesday, 15:00-16:00 - 30.95 Audimax B

Semi-plenary talk Lahrichi

Stream: PC Stream
Semi-plenary session
Chair: *Stefan Nickel*

1 - Improving cancer treatment logistics
Nadia Lahrichi

The main cancer treatments are surgery, radiation therapy and chemotherapy. The complexity of the logistical process of scheduling treatment appointments stems from the fact that it involves extremely costly resources, sometimes synchronously. Several due dates (i.e., appointments already scheduled, maximum wait times) and unexpected events such as the arrival of patients requiring urgent palliative care add to the difficulty. This talk will investigate how can simulation and optimization models help improve the efficiency of cancer treatment centers and share experiences on patient booking, physician scheduling, and capacity assessment. All projects are conducted in close partnership with hospitals and rely on real data.

■ WD-04

Wednesday, 15:00-16:00 - 10.11 Hertz-Hörsaal

Semi-plenary talk Kaibel

Stream: PC Stream
Semi-plenary session
Chair: *Christina Büsing*

1 - Steiner Cut Dominants
Volker Kaibel

For a subset of terminals T of the nodes of a graph G a cut in G is called a T-Steiner cut if it subdivides T into two non-empty sets. The Steiner cut dominant of G is the Minkowski sum of the convex hull of the incidence vectors of T-Steiner cuts in G and the nonnegative orthant. It is the polyhedron that is naturally associated with the problem of finding a minimum T-Steiner cut in G w.r.t. nonnegative edge weights. While it is well understood for two terminals (s-t-cuts), for larger sets T no inequality descriptions have been known so far despite quite some efforts that have been spent into investigating this problem for T being the complete node set of G (global cuts). In this talk we derive such descriptions for all graphs and up to five terminals. Moreover, we prove that for each number k there is a finite list of inequalities from which one can derive by means of iterated applications of two simple operations inequality descriptions of the Steiner cut dominant for every graph and up to k terminals. We furthermore introduce the concept of the Steiner rank of a facet of a global cut dominant and classify the facets of Steiner rank at most five. Via blocking duality those results yield corresponding results for the vertices of the subtour elimination polytope that is most relevant in the context of the traveling salesman problem.

The talk is based on joint work with Michelangelo Conforti (U Padova).

Wednesday, 16:30-18:00

■ WE-02

Wednesday, 16:30-18:00 - 30.95 Audimax A

Tutorial: Power Systems Operations and Modeling

Stream: Energy and Environment, sponsored by EnBW
Tutorial session
Chair: *Veit Hagenmeyer*

1 - Unbalanced three-phase power flow models, analysis, and optimization
Steven Low

Single-phase power flow models are inadequate when transmission or distribution lines are not transposed or equally spaced or when loads are unbalanced. This tutorial consists of three parts, on unbalanced three-phase (1) models, (2) analysis, and (3) optimization. A network consists of three-phase devices connected by three-phase lines. In part 1, we first present the internal and external models of three-phase devices such as voltage sources, current sources, power sources, and impedances in Y and Δ configuration. We then describe three-phase line models and the relationship between terminal voltages, currents and powers in an unbalanced three-phase network. In part 2, we formulate a general three-phase analysis problem using an overall network model composed from three-phase component models presented in Part 1. When the network is balanced, we show that the network reduces to per-phase networks and prove that its analysis is equivalent to a per-phase analysis. When the network is unbalanced but has a certain symmetry, we can transform the network to a sequence coordinate in which the network becomes decoupled even if the phases are coupled in the original (phase) coordinate. In part 3, we formulate unbalanced three-phase optimal power flow problems, both in bus injection models and branch flow models. We show how to represent them as nonconvex quadratically constrained quadratic programs. We explain their semidefinite relaxations and discuss some of their analytical properties when the network is three-phase radial.

■ WE-03

Wednesday, 16:30-18:00 - 30.95 Audimax B

Column Generation

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Marco Lübbecke*

1 - A Heuristic Column Generation Approach for the Stochastic Bin Packing Problem
John Martinovic, Nico Strasdat, Jean-François Côté, Vinícius Loti de Lima

The stochastic bin packing problem (SBPP) is an extension of the well-studied classical bin packing problem with respect to imperfect information on the item sizes. From a practical point of view, the latter are typically represented by (stochastically independent) normally distributed random variables with given means and variances. In this scenario, the SBPP requires to determine the minimum number of bins needed to pack all the items, with the risk of overloading a bin not exceeding a certain tolerable limit. Such computations are of high relevance in server consolidation applications, where decisions have to be made before witnessing the true item characteristics. The resulting integer optimization problems are generally nonlinear and therefore difficult to solve. For this reason, previous approaches from the literature can only handle small instance sizes exactly. In this work, we present a column generation algorithm using heuristic information and near-optimal solutions of the associated (challenging) pricing problems. Based on numerical tests, we show that in most cases this heuristic approach already leads to an optimal solution, so that much larger instance sizes can now be dealt with in reasonable time.

2 - Facilitating branch-and-price development and experiments
Marco Lübbecke, Erik Mühmer

We have been developing a generic decompostion solver since more than a decade, with many authors contributing to the theoretical and implementational effort. We also witness many successful applications of branch-and-price to a vast variety of (discrete) optimization problems. Yet, the combination of both, testing a generic solver in order to assess the potential of a decomposition based approach and, if promising, the onwards implementation of a specialized code based on the generic one is a rare event, at least according to our observations.

We have therefore focused our development efforts in the recent past on lowering the entry barrier. There is an improved documentation (which is always an issue in academic software), we provided new interfaces, e.g., to Python, and offer experimentation scripts and evaluation facilities to run (generic) computational experiments. This is a long, maybe neverending journey, and we are well aware that we are not "done" yet. In that sense this presentation is also meant as an invitation for bringing items for the wishlist, and maybe even for contributing to the project.

3 - (Strong) branching in branch-and-price
Oliver Gaul, Erik Mühmer, Marco Lübbecke

Many branching rules have been proposed in branch-and-bound (B&B), one of which is (full) strong branching. In order to assess the actual dual bound improvement when branching on a certain variable, one solves the corresponding linear programming relaxation. This significantly reduces the tree size, but the computational burden is so large that strong branching is not used by default, and if it is used, then in restricted ways (like not probing all variables, not solving the linear relaxations to optimality, etc.). Strong branching can also be combined with other heuristics, resulting in some of the most successful branching candidate selection heuristics for general problems, like hybrid pseudocost/strong branching or reliability branching.

As evaluating individual nodes in branch-and-price (B&P) generally takes longer than in B&B due to column generation, both the cost of using strong branching and the benefits of having a small tree are amplified. This potentially changes the relative performance of existing branching candidate selection heuristics, and gives opportunity for new ones. One such heuristic is hierarchical strong branching (known from the literature for particular problems), which combines other heuristics with strong branching with and without column generation in a hierarchical fashion. We extend hierarchical strong branching, and among other things combine it with hybrid pseudocost/strong branching and reliability branching. Our implementation is done in the generic, that is, problem unspecific branch-and-price solver GCG. This allows us to evaluate and compare the performance of various strong branching-based and several other candidate selection heuristics, both for original variable branching and Ryan-Foster branching.

4 - Branch-Price-and-Cut-Based Solution of the Order Batching Problem
Julia Wahlen, Timo Gschwind

In this talk, we present the first full-fledged branch-price-and-cut (BPC) approach for the order batching problem (OBP) in warehousing. Given a set of customer orders, each comprising a list of items to be picked, the OBP consists of grouping all orders into batches such that the total distance traveled to pick all items is minimized while respecting the pickers capacity and assigning each order to exactly one batch. We consider a rectangular warehouse with parallel aisles of equal length and width. The storage locations of the items and the routing strategy used by the pickers to traverse the warehouse are assumed to be fixed a priori. The routing strategies considered are return, traversal, midpoint, largest gap, combined as well as exact routing. Starting from a set partitioning formulation of the OBP, 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. Strong 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. Computational tests indicate that the proposed BPC leads to a significant speedup compared to the state of the art.

■ WE-04

Wednesday, 16:30-18:00 - 10.11 Hertz-Hörsaal

Solution Methods for Multistage Stochastic Programming

Stream: Continuous and Global Optimization
Invited session
Chair: *Christian Füllner*

1 - Adaptive partition-based SDDP algorithms for multistage stochastic linear programming with fixed recourse

Murwan Siddig, *Yongjia Song*

We present an algorithm for solving multistage stochastic programming (MSP) problems where the recourse matrix and cost vector are fixed and the stochastic process is assumed to be stage-wise independent. Our algorithm integrates the Adaptive Partition-based Approach for solving two-stage stochastic programs with the Stochastic Dual Dynamic Programming (SDDP) algorithm. We present two main variants of the proposed algorithm: (1) Refinement-outside SDDP strategy, where the SDDP algorithm is used iteratively to solve coarse scenario trees, induced by the partitions, and the partitions are refined at intermediate steps; and (2) Refinement-within SDDP strategy, where the partitions are refined in conjunction with the machinery of the SDDP algorithm. We performed computational experiments on a hydro-thermal power generation planning problem. The numerical results show the effectiveness of the Refinement-outside SDDP strategy compared to the standard SDDP algorithm, and the Refinement-within SDDP strategy.

2 - Parallel Computing Applied to Stochastic Dual Dynamic Programming

Daniel Avila, *Anthony Papavasiliou*, *Nils Löhndorf*

We study different parallelization schemes for the stochastic dual dynamic programming (SDDP) algorithm. We study the effectiveness of these methods in terms of achieving tight optimality gaps, as well as the scalability properties of the algorithms with respect to an increasing number of CPUs. In particular, we study the effects of the different parallelization strategies on performance when increasing the number of Monte Carlo samples in the forward pass and demonstrate through numerical experiments that such an increase may be harmful. Furthermore, we propose a parallel SDDP variant using experience replay - a batch learning technique from reinforcement learning. We demonstrate the superiority of the algorithm over conventional SDDP by benchmarking it against PSR's SDDP software using a large-scale instance of the long-term planning problem of inter-connected hydropower plants in Colombia. We find that SDDP with batch learning is able to produce tighter optimality gaps in a shorter amount of time than conventional SDDP. We also find that batch learning improves the parallel efficiency of SDDP backward passes.

3 - Dynamic SDDiP in Multistage Stochastic Unit Commitment

Leo Schleier, *Christian Füllner*, *Steffen Rebennack*

Multistage stochastic mixed-integer linear problems (MSMILPs) are non-convex, usually of large scale, and hard to solve. This calls for decomposition approaches to keep the solution process computationally tractable. Recently, the set of decomposition approaches has been extended by stochastic dual dynamic integer programming (SDDiP). Constructing outer approximations of the value functions using so-called Lagrangian cuts, this method can solve MSMILPs with binary state variables exactly. Performing a binary approximation of general mixed-integer state variables, SDDiP is applicable to a broader class of MSMILPs. The binarization of variables is fixed and carried out in advance. However, this requires knowledge about problem-specific parameters which may be hard to gain in practice. A recent proposal is to use a more sophisticated binarization approach where the approximation is applied temporarily and refined dynamically. For this purpose, by projection, non-convex Lagrangian cuts are created that are applicable in binary and mixed-integer state space. The present work combines SDDiP and the dynamic binarization approach in a dynamic SDDiP algorithm. The method is evaluated on multistage stochastic unit commitment problems. First computational results show that the algorithm can be favorable in solving problems that are otherwise computationally intractable. On the other hand, the non-convex representation of Lagrangian cuts itself is an undeniable computational bottleneck. Several strategies to mitigate this adverse effect are being discussed.

4 - A new framework to generate Lagrangian cuts in multistage stochastic mixed-integer programming

Christian Füllner, *Andy Sun*, *Steffen Rebennack*

Based on recent advances in Benders decomposition and two-stage stochastic integer programming we present a new generalized framework to generate Lagrangian cuts in multistage stochastic mixed-integer linear programming (SMILP). This framework can be incorporated into decomposition methods for multistage SMILPs, such as the stochastic dual dynamic integer programming (SDDiP) algorithm. We show how different normalization techniques can be applied in order to generate cuts satisfying specific properties with respect to the epigraph of the value functions, e.g. having a maximum depth or being facet-defining. In addition, we show that the proposed methodology can be extended to cases where regularized value functions are considered. We provide results for the computational comparison of our proposed cut generation approach with existing techniques from the literature, as well as the comparison of different normalization techniques within our framework.

■ WE-05

Wednesday, 16:30-18:00 - 11.10 Engelbert-Arnold-Hörsaal (EAS)

Design of Resilient Supply Chains

Stream: Supply Chain Management
Invited session
Chair: *Teresa Melo*

1 - Resilient network design with disruption uncertainty and lead times

Daniel Müllerklein, *Pirmin Fontaine*

On October 2018, low water levels on the river Rhine, one of Europe's most important waterways, forced transportation to a standstill and major companies to issue profit warnings due to production losses and higher logistics cost. In increasingly complex and global supply chains, reliable transports are needed to supply products from various inbound suppliers in a cost-efficient way. However, transportation routes are prone to disruptions, such as hurricanes, low water levels or port shutdowns, resulting in transportation stops or price increases. Resilience policies, that increase the costs in steady state, aim at increasing the capability of a network to withstand, adapt and recover from disruptions. For a cost-optimal use, it is necessary to determine the optimal mix of strategic, tactical, and operational policies against the "do-nothing" scenario of risk taking under the uncertainty of disruption occurrence and impact.

We develop a decision-support model that decides on the optimal mix of resilience policies, such as multi-sourcing, inventory increase, or operational re-routing, for a two-echelon inbound supply chain with transportation disruption uncertainty to minimize total costs. The problem setting is modeled as a two-stage stochastic mixed-integer linear program (MILP).

We present a case study for the inbound supply chain design of a company with recurring transportation uncertainty on the main transportation mode. Taking disruption and lead time effects into account, a mix of resilience policies leads to cost advantages compared to the base case of risk taking. If operational re-routing as well as strategic and tactical policies are mixed, cost improvements of up to 15% can be achieved.

2 - Multi-Product Supply Chain Performance Optimization under Demand Uncertainty

Asrat Mekonnen Gobachew, *Hans-Dietrich Haasis*

A supply chain is a complex system featuring dynamism and uncertainty in its operations. A stochastic optimization method is one of the approaches that can be employed to solve this complex system. In this study, a supply chain performance optimization under demand uncertainty is considered. Overall supply chain cost is assumed to be a measure of supply chain performance measurement. The study deals with the problem of multi-product, multi-level supply chain networks, and a stochastic optimization approach is used to solve the problem. A mixed-integer linear programming (MILP) model that minimizes the overall supply chain cost is developed. The model determines the location, number, and capacity of distribution centers as well as distribution links among the main distribution center, local distribution centers,

and demand points. Demand points exhibit uncertain demand patterns for the products. For its validation, the model is applied to a case of a pharmaceutical distribution network in Ethiopia. The result of the stochastic model is compared against the deterministic counterpart of the model, and the performance of the existing distribution network.

3 - Two-echelon distribution network redesign under flexible conditions

Teresa Melo, Isabel Correia

E-commerce is growing at a fast pace. This trend is gradually driving retailers to shift from typical warehouse rental contracts with rigid conditions and long-term commitments to flexible alternatives that provide storage space on demand. This strategy gives retailers the ability to respond dynamically to variations in demand, thereby improving customer service. We address this trend by considering a two-echelon, multi-commodity distribution network operated by a retailer and whose configuration can be changed over a multi-period planning horizon. Location decisions concern the intermediate facilities and are framed by flexible and scalable conditions. Accordingly, the retailer needs to decide which company-owned facilities should be retained, and where, when and for how long new facilities should be leased from a set of potential sites with given capacities. In addition to location decisions, also procurement, inventory, and distribution decisions need to be made to satisfy customer demand at minimum total cost. We develop a mixed-integer linear programming formulation for this problem and propose various families of additional inequalities that prove to be very useful to find high-quality solutions. To measure the impact of the new business model, we also study alternative approaches with limited flexibility and scalability that are frequently encountered in practice. Our computational study gives useful insights on the trade-offs achieved by each of the different approaches with respect to total cost, network redesign decisions, and various logistics functions.

4 - Bi-Objective Supply Chain Network Design with Modal Choice and Inventory Pooling Effect

Eberhard Schmid

One important planning task in Supply Chain Management (SCM) is Supply Chain Network Design (SCND). Within SCND, the decision maker's task is to decide upon locations for production or distribution facilities, product allocations to warehouses and factories, customer allocations and the choice of the transport modes. Clearly, these decisions do not only have an impact on the economic performance of the supply chain but also on environmental indicators like the emission of CO2. So does the choice of a specific location influence transportation cost as well the emissions of CO2. The number of warehouses used determines the amount of stock to be hold in the warehouses. The transportation mode used not only has an influence on emissions, but also influences the cycle stock since different transport modes are associated with different shipment sizes. Further, since transport modes differ in transportation time, it also influences safety stocks in warehouses. Against this background, the aim of this paper is to develop a bi-criteria network optimisation model, which is able to respect the trade-offs described above. After describing the research gap in the literature, we present a bi-objective Mixed Integer Nonlinear Programming model minimising total costs and transport-based CO2 emissions. Further, we describe a solution procedure, which includes the conversion into a mixed integer conic quadratic optimisation model. Finally, we demonstrate the applicability within a case study and discuss computational and managerial insights.

■ WE-06

Wednesday, 16:30-18:00 - 10.91 Redtenbacher-Hörsaal

Decision Support under Uncertainty in Short-Term Power Systems

Stream: Decision Analysis and Support
Invited session
Chair: *Jochen Gönsch*

1 - Optimal Trading for Renewable Energy Portfolios on Short-Term Power Markets

Simon Hirsch, Florian Ziel

Short-term electricity markets are crucial for the market-based integration of intermittent renewable energy. In Europe, these markets are usually a series of auctions, followed by a continuous intraday market. Our research focuses on the optimal trading problem for renewable energy producers across the various sequential markets. The academic literature so far (a) essentially concerns the optimization of combined renewable and dispatchable asset portfolios, thus alleviating the joint volume-price risk of renewable energy assets arising from the negative correlation between prices and volumes, (b) disregards the structural breaks between auction-based spot markets and continuous intraday markets, and (c) utilizes simplified price processes, while the forecasting community has found complex processes to reflect prices and volatility better. We bridge these gaps and model the structural breaks between markets, as well as within markets together with the influence of liquidity, market impact, and trading costs for optimizing a renewable energy portfolio under joint volume-price risk. Our work draws from the econometric literature on electricity markets, quantitative finance, and operations research. In a case study, we consider a historical evaluation of the German Market to evaluate the value-added of increasingly complex models and analyze the impact of market features such as XBID/SIDC and time-varying volatility on the optimal decision for a renewable energy producer. The general approach is transferable to other European electricity markets.

2 - Integrated day-ahead and intraday self-schedule bidding for energy storage systems using approximate dynamic programming

Jochen Gönsch, Benedikt Finnah, Florian Ziel

Most modern energy markets trade electricity in advance for technical reasons. Thus, market participants must commit to delivering or consuming a certain amount of energy before the actual delivery. In Germany, two markets with daily auctions coexist. In the day-ahead auction market, the energy is traded in 60-minute time slots, which are further partitioned into 15-minute time slots for the intraday auction market. Because of the slow ramp-ups of nuclear and fossil power plants, these price-makers trade mostly in the day-ahead market. Only the residual energy is traded in the intraday market, where the market prices fluctuate substantially more. These fluctuations as well as the expected price difference between these markets can be exploited by fast ramping energy storage systems. We address the decision problem of an owner of an energy storage who trades on both markets, taking ramping times into account. Because the state variable of our dynamic programming formulation includes all features of our high-dimensional electricity price forecast, this problem cannot be solved to optimality. Instead, we use approximate dynamic programming. In a numerical study based on real-world data, we benchmark the algorithm against an adapted state-of-the-art approach from literature and an expectation model with a receding horizon. Furthermore, we investigate the influence of the price forecast on expected profit and demonstrate that it is essential for the dynamic program to capture the high dimensionality of the price forecast to compete with the expectation model, which does not suffer from the curses of dimensionality.

3 - Using Open Access Power Plant Data for Stochastic Availability Modelling

Maike Spilger, Christoph Weber

In future energy systems with a high share of renewable energies, the need for flexibility from dispatchable power plants to balance demand and generation of electricity will increase. As a result of the decarbonization of energy systems, electricity demand and its dependence on weather is increasing, and simultaneously dispatchable power plants have to phase out due to economic competition and political regulations. The availabilities of dispatchable power plants are affected by technical failures, operational errors, and context factors and are a key uncertain factor that has to be considered in decision-making problems especially when analyzing security of supply issues.

In our contribution, we develop an approach to model the uncertainty of available dispatchable power plants. We make use of a large publicly available dataset from the ENTSO-E Transparency Platform in order to obtain empirically validated parameters for stochastic generation adequacy studies. We develop a semi-Markov model (SMM) to simulate the availability of dispatchable power plants based on data. The standard SMM is characterized by the distribution of durations per operating state and the probability of state transitions. We extend the model to describe the dependency of availabilities and unavailabilities on technology groups, regions, and seasons. In an application, we use five years of ENTSO-E data on more than 1,500 units to determine empirical parameter estimates. In contrast to other existing studies, we furthermore simulate the availability of individual power plants across time steps based on the empirical parameter estimates. We then assess

the quality of the SMM simulations compared to observations based on selected statistical indicators.

4 - Preference Elicitation for the Ordered Weighted Averaging Criterion
Werner Baak, Marc Goerigk

The presented paper explores methods of preference elicitation for the ordered weighted averaging (OWA) criterion. Our aim is to identify the decision maker's weights that define OWA. We assume that we have a set of examples where the decision maker has chosen a preferred solution by hand. We then generalize these examples to determine decisions for new problems. We propose and compare two approaches to determine OWA weights. The first is an optimization-based model, where weights are determined by solving a sequence of mixed-integer linear programs. The second is a machine learning model to predict weights using a regression approach. By measuring the average distance between true OWA weights and estimated weights, we conclude that the performance of optimization-based models is improving with an increasing size of given examples, i.e., these models make effective use of the given information; whereas the regression models can perform better when only few examples are provided.

■ WE-07

Wednesday, 16:30-18:00 - 10.91 Grashof-Hörsaal

Graphical Optimization Models

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

1 - Novel heuristics for Compiling Approximate Decision Diagrams for Combinatorial Optimization
Mohsen Nafar, Michael Römer

Given a Dynamic Programming formulation of a Combinatorial Optimization Problem (COP), it is possible to represent its solution space using a Decision Diagram (DD). Specifically, a DD is a layered directed acyclic graph in which nodes correspond to states and arcs to decisions inducing transitions between states. If the decision variables of the COP are binary, then the associated decision diagram for it is a binary DD and if the decision variables are integer values, then its associated DD is a multi-valued DD. An application of DDs is to obtain bounds for the COP. For this purpose, different types of decision diagrams are being used where the size of them are linear and are called restricted DD and relaxed DD. Suppose the COP is a maximization (minimization) problem, then a restricted DD gives a lower (upper) bound and a relaxed DD gives an upper (lower) bound on the optimal solution of the problem. One advantage of using a relaxed DD is that it provides a discrete relaxation of the problem. In particular, these bounds can be used in a branch and bound algorithm to solve the problem to optimality. The most popular approach for compiling relaxed and restricted DDs proceeds layer by layer in a top-down fashion, using simple heurisitics for deciding which nodes to merge (in case of relaxed DDs) and to remove (in case of restricted DDs). In this talk, we propose a more complex heuristic relying on building approximate equivalence classes. In preliminary experiments, we applied our heuristic on one and multi dimensional Knapsack problems. Our computational results show that for the majority of the instances, the bounds obtained by our heuristics is better than the bounds obtained by restricted and relaxed decision diagrams compiled using the traditional heuristics.

2 - Peel-and-Bound: Generating Stronger Relaxed Bounds with Multivalued Decision Diagrams
Isaac Rudich, Quentin Cappart, Louis-Martin Rousseau

Decision diagrams are an increasingly important tool in cutting-edge solvers for discrete optimization. However, the field of decision diagrams is relatively new, and is still incorporating the library of techniques that conventional solvers have had decades to build. We drew inspiration from the warm-start technique used in conventional solvers to address one of the major challenges faced by decision diagram based methods. Decision diagrams become more useful the wider they are allowed to be, but also become more costly to generate, especially with large numbers of variables. We present a method of peeling off a subgraph of previously constructed diagrams and using it as the initial diagram for subsequent iterations that we call peel-and-bound. We test the method on the sequence ordering problem, and our results indicate that our peel-and-bound scheme generates stronger bounds than a branch-and-bound scheme using the same propagators, and at significantly less computational cost.

3 - Learning to Build Small State-Expanded Networks
Michael Römer

Mixed-integer linear programming formulations based on flows in state-expanded networks in which nodes correspond to states and edges represent state transitions often have very strong LP relaxations and have been used with considerable success in various applications. One of the challenges of these formulations is that for large-scale problems, the size of the model instances become huge. In previous work, we proposed to use machine learning to guide the reduction of large state-expanded networks based on learning from optimal solutions for sets of similar problem instances. In this talk, we propose an approach that does not rely on such offline-training but that uses machine learning to heuristically filter and iteratively improve state-expanded network models based on initial approximate networks. We demonstrate the efficiency of this approach with instances from different types of resource scheduling problems, showing that in many cases, optimal or near-optimal solutions can be obtained in a fraction of the computing time needed for solving the full state-expanded network models.

■ WE-08

Wednesday, 16:30-18:00 - 10.50 HS 102

Optimization models for large-scale energy storage systems

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Bismark Singh*

1 - Optimal Design and Operation of Community Hydrogen Generation and Storage Applications
Frederik vom Scheidt, Manuel Katholnigg, Armin Golla

With the introduction of a national hydrogen strategy, Germany aims to decrease the dependency on fossil gas and reach its climate targets. Part of this strategy is the generation of green hydrogen through electrolysis. However, it is debated whether such systems can be applied efficiently. In local energy communities, hydrogen generation and storage systems offer the potential to reduce seasonal imbalances between renewable electricity generation and consumption. Efficient fuel cells allow hydrogen systems to provide both heat and electricity, which can reduce the carbon footprint of communities. In this study, we propose a linear optimization program to investigate the integration of a 30-bar and a 300-bar hydrogen storage in an energy community. Furthermore, components such as a battery, buffer storage, gas boilers, electrolyzers, a fuel cell, heat pumps, photovoltaic and solar thermal systems are modeled. We determine optimal component configurations in various scenarios, including German subsidy policies, electricity price increases, partial energy self-sufficiency, and purely ecological optimization. To assess the functionality of the system, we evaluate an operational strategy that uses a receding-horizon control algorithm. According to our findings, a hydrogen storage system proves to be a valid option when purely ecological optimization is performed or partial self-sufficiency is targeted in an exemplary community with 19 households. The proposed operational strategy demonstrates the potential to decrease the carbon footprint and dependency on fossil fuels of the community. Thereby, we contribute to a clearer distinction of cost-efficient application areas for seasonal hydrogen storage and support the application of the national hydrogen strategy.

2 - Optimal Energy Storage System Operation under Uncertainty
Sarah Wimmeder

Due to the increasing share of renewable energies the demand for power storage has been growing significantly in recent years. This development opens a wide variety of possible battery applications at generation as well as consumption level. The focus of this paper is on optimally operating an energy storage system by dynamically adjusting electricity storage decisions in response to randomly evolving state variables, such as electricity demand, photovoltaic generation and electricity prices. To quantify the value of integrating a battery storage

into the system, a multistage stochastic programming model is formulated with the objective to minimize the expected total electricity costs over a finite planning horizon. It provides optimal charging and discharging decisions under uncertainty at each stage of the decision horizon. As a consequence of the so called 'curse of dimensionality', stochastic dynamic decision problems are really challenging as it implies that the complexity of the problem increases exponentially in the number of states, and that in general no solution algorithm which converges towards an exact solution in polynomial time exists. To guarantee computational tractability, the problem is solved by a combination of stochastic dual dynamic programming and a quantization method which approximates the input data by a discrete scenario lattice. This method is referred to as approximate dual dynamic programming (ADDP). To assess the added value of the stochastic solution, the results obtained by the ADDP method are compared to results assessed by a deterministic approach. We find that the stochastic optimization approach is quiet promising. Compared to conventional optimization, stochastic optimization enables more advantageous decision making.

3 - Identifying critical demand periods in capacity planning for power networks including storage
Philipp Hahn, *Andreas Bley*

We consider a basic capacity planning problem for power networks including storage. Given a bidirected graph and a time series of external demands and supplies, we seek for integer link and storage capacities and load profiles for all storage units, such that the resulting node balances permit a single commodiy flow in each time step. This problem arises, for example, in offshore wind power systems planning, where changing wind conditions lead to varying demand scenarios for the power network and (battery) storage can be used to buffer peak supplies and demands. In this application, typically timely resolutions of one hour or finer for a full year are considered, which leads to optimization models that are extremely large and hard to solve. Time series aggregation methods are commonly used to reduce the size of these models. Typically, the complete time horizon is sliced into periods of fixed size (e.g. days or weeks), clustering methods are used to choose a small set of representative periods, and eventually a much smaller model involving only these representative periods is solved. However, the most critical situations, where demands or supply are most extreme and the effects of storage are most important, are typically not covered by the representative periods. To overcome this drawback, critical periods representing such situations can be added to the model. In this talk, we present a new method to identify such critical periods based on principal component analysis (PCA) and convex hull computations. We discuss different strategies and compare solution qualities and times of the reduced models to the original ones. Results are presented for instances derived from power systems planning projects and from benchmark library problems.

■ WE-09

Wednesday, 16:30-18:00 - 10.50 Raum 604

OR for Enhancing Flexibility of Distribution Systems

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Nastaran Naseri*

1 - Demand Response Analysis Framework (DRAF): An open-source multi-objective decision support tool for decarbonizing local multi-energy systems
Markus Fleschutz, *Markus Bohlayer*, *Marco Braun*, *Michael D. Murphy*

A major barrier for companies to invest in clean energy technologies and services is the lack of knowledge about their impact on the company's profitability and carbon footprint due to their complex economic and technical interactions. To exploit the full decarbonization potential of Local Multi-Energy Systems (L-MESs) and to reduce investment barriers decision support tools are needed that integrally consider different fields of decarbonization measures such as load flexibility, electrification, and renewable energy sources. We, therefore, present the open-source Python package Demand Response Analysis Framework (DRAF), that provides decision support to decision-makers of L-MESs by integrally optimizing the design and operation of clean energy technologies considering demand-side flexibility. It quantifies decarbonization and cost reduction potentials using multi-objective mixed-integer linear programming and provides optimal scenarios regarding costs, emissions, or Pareto efficiency. DRAF supports all steps of an energy system optimization process: Time series analysis, model generation through component templates, parameter preparation such as dynamic carbon emission factors, scenario generation, and interactive plotting. We demonstrate the features of DRAF via case studies based on real-world industrial examples.

2 - Aggregator-based optimization of the deployment of decentralized flexibility under consideration of technological and economic restrictions
Kai Hoth, *Béla Wiegel*, *Jonas Hasmann*, *Kathrin Fischer*

The energy system transformation towards decentralized and renewable energy resources (DERs) is inevitable in order to mitigate climate change. New operational concepts arise as a consequence of structural system changes and the ongoing digitization of energy systems. Research in the field of transactive energy gives increasing importance to energy markets, not only from an economic perspective, but also as part of an approach for efficiently and resiliently operating grids. Aggregators help to bring the DERs' potential for flexibility to the market. However, an aggregator's decision on how to employ a large number of different kinds of flexible resources, considering the respective technological properties and also economic conditions of the flexibility providers, is a complex problem.

In this work, mixed-integer linear programming is used to develop and implement an optimization model for this problem. The model is applied in a case study consisting of a distribution grid with a large number of prosumer households with load and generation profiles and individual flexible assets. The new research contribution lies in the high level of detail and the combined consideration of different flexibility types such as heat pumps, electric vehicles, battery storages and time-shiftable loads. The integration of a flexibility framework which regulates the aggregators' degrees of freedom in deploying their customers' flexibility is a further innovation compared to existing literature.

The numerical results from the case study give insights regarding the utility that the different types of flexibility provide to the aggregator, to the households and to the overall grid resilience. Further analyses validate the efficiency of the flexibility framework.

3 - Optimal Design of Building Energy Supply - A Case Study
Elisabeth Halser, *Elisabeth Finhold*, *Neele Leithäuser*, *Karl-Heinz Küfer*

Building energy supply is a main source of greenhouse gas emissions. Therefore, severe reduction in this field is inevitable. In our case study we focus on design and operation of a new office building's energy supply, where we combine known concepts to one decision support workflow.

The planned office building is located in Kaiserslautern as an annex to an already existing office complex, where heating and cooling loads of the past years are known in hourly resolution. Cooling loads in this case are almost exclusively caused by computing centers in the building.

We started with a draft of the building cubature and building materials and used the approach of a thermal network to simulate hourly heating loads for different climate scenarios. A network model of the already existing building was used for calibration. The generated hourly heating loads together with extrapolated cooling loads from the existing complex are then used to find out the optimal and robust selection of generators (heating, cooling, electrical power), thermal storages and their dimensions for the new building. For that purpose, we modeled and solved the problem as a bicriteria Mixed Integer Problem (MIP), where costs and carbon footprint are minimized simultaneously.

4 - Towards A Best-Effort Grid
Nastaran Naseri, *Yashar Ghiassi-Farrokhfal*, *Steffen Rebennack*, *Wolfgang Ketter*

Electricity grids increasingly incorporate highly variable distributed renewable energy sources and power-hungry but stochastic electric vehicles. This creates uncertainty in short-term supply-demand matching and hence, unreliability in electricity grids. Utilities rely on one or both of two expensive solutions to mitigate this unreliability: markets for reserve generation and load flexibility and grid reinforcement. This imposes operational and investment costs that, in most jurisdictions, are borne by utilities or retailers. Although both costs are eventually recovered from consumer tariffs, these cost transfers are often inaccurate, sometimes unfair, and ignore the fact that consumers with local

storage can ride out transient episodes of grid unreliability with no loss of comfort. We propose an alternative approach where the grid is explicitly allowed to be unreliable for customers who have local storage. If a utility's customer has local storage, allowing it to ride out outages with no loss of comfort, grid unreliability is masked, and it can be 'best-effort.' Thus, utilities or aggregators can shift the risk of unreliability and their costs to end-consumers through proper tariff mechanisms. Using stochastic programming, we develop tariff mechanisms that create a win-win scenario for both utilities and customers because utilities pay less for grid reliability and customers pay less for their energy. Moreover, utilities can benefit from participating in a local flexibility market, trading the battery capacity acquired from customers through tariffs. Our work contributes to the literature by proposing a new business model for electricity utilities, incentivizing storage installation in residential settings, and creating a greater potential for grid flexibility.

■ WE-10

Wednesday, 16:30-18:00 - 20.30 SR 0.014

Multi-echelon routing problem & Disaster management

Stream: Logistics
Invited session
Chair: *Lorena Reyes-Rubiano*

1 - The Grey Zone Two-Echelon Vehicle Routing Problem with Customer to Parcel Locations and Low-Pollution Vehicles for Inner-city Logistics

Edgar Ricardo Silva Russi

This study addresses the two-echelon vehicle routing problem with grey areas and C2P (customer to parcel) stations. This problem arises in the search for new sustainable delivery schemes for online shopping and last mile distribution in urban areas. In the considered problem, first echelon Internal Combustion Engine Vehicles (ICEV) start from a single warehouse and transport goods to first echelon direct delivery customers and to C2P stations where the first echelon C2P customers can directly pick up their goods by themselves. These first-echelon C2P stations can also serve as satellites where synchronization between first-echelon ICEVs and second-echelon alternative fuel vehicles (AFVs) departing from the second-echelon warehouse is achieved to reduce waiting times. From there, the second-echelon AFVs will serve direct delivery customers and drop off goods at the second-echelon C2P stations where second-echelon C2P customers can pick up their goods themselves. Customers in the grey area belong to both the first and second echelon and can therefore be served by any vehicle, thus reducing the long trips of the second echelon vehicles by optimizing the routes of both echelons. The two-echelon vehicle routing problem with grey areas and C2P (customer to parcel) stations aims to reduce transportation costs and environmental and social impact. This study proposes a literature review on the subject and a MILP formulation to model the described problem.

2 - Combined Distribution Systems for City Logistics

Barbara Himstedt, Frank Meisel

Reliable, efficient and environmentally friendly delivery despite of congested streets, surging volumes of shipments and increasing customer requirements is what parcel service providers are supposed to achieve in urban areas. This can hardly be realized by means of conventional delivery with diesel vans. In recent years, great efforts have therefore been made in researching and implementing alternative delivery concepts, such as the installation of parcel lockers, distribution with cargo bikes and autonomous delivery by robots or drones. So far, however, corresponding studies usually consider only one delivery system at a time. In order to compare these different distribution systems and to find out whether and in which configuration they can be combined suitably and effectively, we propose in this talk a MILP model that combines them in a modular way. Based on a 2-echelon delivery system, vans are used to carry the shipments into the city area, where they are delivered to the customers by smaller vehicles of various types. Thereby, the model supports to include first echelon vehicles into final delivery, and also to use them for transferring other small-sized delivery vehicles to the distribution area. Preliminary results from realistic simulations of small instance size indicate notable cost savings particularly in using autonomous robots and drones, even considering multiple cost structures, different road infrastructures and varying combinations of delivery vehicles. For solving larger instances, we propose and evaluate an Adaptive Large Neighbourhood Search Heuristic.

3 - Dealing with Routing Decisions in Disrupted Networks: Immediate Post-disaster Phase

Lorena Reyes-Rubiano, Jana Voegl, Patrick Hirsch

Disasters are unexpected events characterized by a negative impact on lives lost and high logistical costs during and after the disaster. The impact of a disaster can be estimated by analyzing the affected population and the magnitude of the disaster. We are interested in determining strategies to deal with the impact of a disaster on accessibility to the affected people. Disasters generate collapsed bridges or blocked roads which hinder the relief of the affected population. We propose a labeled network to determine the relevance of each connection in terms of accessibility to the affected people. The deployment of humanitarian aid is mainly done on the ground, trying to reach the most vulnerable population. Routing decisions generally depend on finding the shortest route to reach the most vulnerable people. However, this criterion could lead the humanitarian aid to blind spots and visit areas that do not reach victims. We propose to analyze the affected area as a network where some arcs are missed (blocked streets) when a disaster occurs, and some nodes are partially or entirely isolated from the network. Our analysis is based on the calculation of a labeled network. Each arc has a label representing its importance regarding accessibility to the network and the victims. Each arc's importance is a measure involving attributes of the network structure and the location of the victims. As missing arcs are detected, the label of all arcs in the network should change, indicating that some arcs are no longer important while the importance of other arcs increases, as long as these arcs are leading to a victim location.

4 - Optimizing Vaccine Distribution in Developing Countries under Natural Disaster Risk

Bonn Kleiford Seranilla, Nils Löhndorf

Vaccinating population of wealthy countries against COVID-19 is moving ahead at full steam, while developing countries are still lagging behind. In many developing nations, vaccination roll-out programs are not only slow but vaccine facility sites are also exposed to the risk of natural disaster, such as flooding, which may slow down vaccination progress even further. It is for this reason that policy-makers in developing countries seek for strategies that hedge against distribution risk in order for vaccination campaigns to run smoothly and without delays. We propose a stochastic-dynamic programming model for selecting vaccination facilities under the risk of failure due to natural disaster. The model integrates a facility location problem of vaccination centre opening with a stochastic-dynamic model of facility failure. To solve the problem, we introduce a novel approximate dynamic programming algorithm, referred to as Shadow Price Approximation, which trains the shadow price of opening a flood-prone facility on historical data, thereby alleviating the need to fit a stochastic model. We trained the model using rainfall data provided by the local government of several major cities in the Philippines which are exposed to multiple flooding events per year. Numerical results demonstrate that the solution approach yields approximately 30-40% lower cost than a baseline approach that does not consider the risk of flooding. We provided the local government with a spreadsheet tool to plan the location of vaccination facilities and found that the proposed approach provides an applicable and practical solution for policy-makers to plan vaccine roll-outs under natural disaster risk.

■ WE-11

Wednesday, 16:30-18:00 - 10.50 Raum 602

Approximation and Scalarizations in Multiobjective Optimization

Stream: Decision Analysis and Support
Invited session
Chair: *Clemens Thielen*

1 - Approximation Methods for Multiobjective Optimization Problems

Stefan Ruzika, Arne Herzel, Clemens Thielen

The exact computation of the set of Pareto optimal points in the objective space (and one corresponding solution in the decision space for each such point) is very difficult for most multiobjective optimization problems because the cardinality of this set may be exponentially large for discrete problems (and is typically infinite for continuous problems). In addition, even deciding whether a single given solution or point is Pareto optimal is computationally hard for most multiobjective problems. Therefore, approximations for multiobjective optimization problems aim at computing a small set of feasible solutions such that every (Pareto optimal) solution is dominated up to a multiplicative factor by some solution in the set. This talk is based on a survey in which we read and analyzed more than 50 articles published between 1979 and 2022. We formally introduce the notion of approximation for multiobjective optimization problems and present basic ideas. We categorize existing approaches, provide a survey of the existing literature, and mention current research trends.

2 - Approximating Multiobjective Optimization Problems: The Power of the Weighted Sum Scalarization
Clemens Thielen, Cristina Bazgan, Stefan Ruzika, Daniel Vanderpooten

Both exact and approximate solution methods for multiobjective optimization problems are often based on scalarizations that transform multiobjective problems into singleobjective auxiliary problems based on procedures that might use additional parameters, auxiliary points, or variables. The resulting scalarized optimization problems are then solved using methods from singleobjective optimization and the obtained solutions are interpreted in the context of the original multiobjective problem.

We present a precise analysis of the approximation quality obtainable for general multiobjective optimization problems by means of the weighted sum scalarization, which is probably the best-known and most widely used scalarization technique in multiobjective optimization. Moreover, we introduce a new multi-factor notion of approximation that is specifically tailored to multiobjective optimization problems and their inherent trade-offs between different objectives. Our results yield essentially tight bounds on the power of the weighted sum scalarization with respect to the approximation of multiobjective optimization problems - both in the common notion of approximation and in the new multi-factor notion.

3 - Similar objective functions in multicriteria optimization
Nils Hausbrandt, Stefan Ruzika

In multicriteria optimization, different objective functions that are in conflict with each other are taken into account. Sometimes the number of objectives to be considered is very large, and the question of reducing this number is crucial. However, this question has rarely been addressed outside the metaheuristic community. In this talk, we consider problems with many objective functions of which some are "similar". This means that their coefficients differ only by a certain factor. We show a reduction in the number of objective functions for these problems that leads to an approximation of the Pareto set. The approximation quality is known and depends on the factor, how far the objective functions deviate from each other. In addition, we address the fundamental question of how to reduce the number of objective functions without changing the Pareto set. Note that this has implications for the difficulty and solution time of multicriteria optimization problems, which we will discuss.

4 - On convex approximation sets for multi-objective optimization problems
Stephan Helfrich, Arne Herzel, Stefan Ruzika, Clemens Thielen

The most common approach to obtain an efficient solution for a multiobjective optimization problem is to specify weights on the objectives, form a weighted sum, and solve the resulting single-objective optimization problem. Hence, the calculation of a solution set that contains, for any such weighted sum problem, an optimal solution is of major importance in multi-objective optimization. However, it is known that the minimum cardinality of such a set can be super-polynomially large for many multi-objective optimization problems. This rules out the existence of polynomial-time exact algorithms for these problems and motivates methods to obtain convex approximation sets - sets of solutions that contain, for any weighted sum problem, a solution whose weighted sum objective is not worse than the optimal weighted sum objective up to an a priori fixed factor.

We propose an approximation method that builds upon an exact or approximate algorithm for the weighted sum problem and returns a convex approximation set. Hereby, an approximation guarantee can be provided that is arbitrarily close to the approximation guarantee of the weighted sum algorithm. Therefore, the proposed method is applicable to a general class of multi-objective optimization problems. In particular, if the weighted sum problem can be solved exactly in polynomial time or if a fully polynomial-time approximation scheme is available, it is a fully polynomial-time approximation scheme for the computation of convex approximation sets.

■ WE-12

Wednesday, 16:30-18:00 - 10.50 Raum 701.3

Combining Mobility and Logistics

Stream: Mobility and Traffic
Invited session
Chair: *Julia Lange*

1 - Planning the scheduled services of a multimodal synchronized two-tier city logistics system
Julia Lange, Teodor Gabriel Crainic, Timo Gschwind, Walter Rei

Due to limited transportation and storage resources in urban areas, future city logistics systems focus on multiple tiers of heterogeneous vehicles and the integration of freight transportation into rail-based mobility networks. Thus, exact synchronization of transportation services of different tiers and freight handovers with minimal spatial requirements are main challenges. With regard to an efficient use of resources, the integration of inbound, outbound and inner-city commodity flows is of increasing importance together with the application of innovative digital transportation-as-a-service ideas. The presented mathematical formulation follows a two-tier service network design approach, where road- and rail-based transportation services with routes, departure time windows and capacities are given. Heterogeneous waiting time policies at customer and handover locations constitute another key characteristic. The goal is to find a selection of operated services, an assignment of all transportation demands and a precise schedule for each service so that travel and waiting times are minimal. With a comprehensive computational study, the effects of different problem characteristics on its complicatedness and solvability by a general state-of-the-art mixed-integer-programming solver are examined and reported. Therein, an elaborate generation procedure and a wide set of new instances for two-tier city logistics service network design are proposed.

2 - Integrating Pooling of Last-Mile Parcel Deliveries with Cargo Bikes into an Agent-Based Travel Demand Model
Jelle Kübler, Anna Reiffer, Peter Vortisch

E-commerce experiences continuous growth, which entails an equal growth in parcel deliveries, counting 21 billion per year in 2019. With more parcels, more delivery vehicles are required, putting an additional strain on the already exhausted environment and transport system, especially in urban areas. Cargo bikes present an emission-friendly and space-saving alternative. They are already used by some CEP service providers (CEPSP) for last-mile delivery. Today, deliveries are split among competing CPESP, each using its own infrastructure. Further redundancies occur as the same address is often served on consecutive days. The white-label approach proposes shared depots and vehicles, reducing redundant infrastructure and delivery trips. Shared decentralized micro-depots support short local delivery tours for cargo bikes. CEPSP and policymakers are keen to understand the impact of different last-mile delivery approaches. Travel demand models are well-established tools for evaluating such policy measures. We use the agent-based travel demand model mobiTopp to simulate the activities and trips of a synthetic population for one week combined with the last-mile delivery extension logiTopp. For our research, we integrate cargo bikes as an alternative mode of transportation for delivery tours and implement two white-label approaches: a single shared depot and multiple decentralized micro-depots. Cargo bike deliveries can be combined with micro-depots for short tours and repeated parcel refilling. Finally, we develop a greedy tour planning algorithm to consider trip pooling across multiple consecutive days by altering the delivery day of certain deliveries. We experimentally evaluate the impact of the presented pooling approaches in a simulation of the survey area of Karlsruhe.

3 - Analyzing Railway Network Capacity using Petri Nets and Mixed Integer Programming

Christopher Szymula, Nikola Besinovic, Karl Nachtigall

Considering railways as a major contributor to sustainable transportation, European decision makers aim for a substantial increase of railway traffic in the upcoming years. However, being already highly utilised, railway networks around Europe might provide only limited reserves for serving these ambitions. Thus, the explicit knowledge about capacity, reserves and bottlenecks is of utter importance. In this work, we develop a mixed integer program (MIP) for railway network capacity assessment. It builds on translating the existing, petri net based railway network occupation model (RNOM) to linear programming. Resultingly, we provide the optimal network occupation while simultaneously optimizing the train order for a given number of trains. The derived MIP is efficiently solved with a row-generation approach. Furthermore, a special case of the model is provided, which explicitly accounts for the networks underlying demand-structure and thus allows for determining its demand-responsive capacity. The provided models are applied as optimization core in the railway network capacity (RNC) framework for network capacity assessment. The results show that computation times were significantly reduced by overcoming some major limitations of the RNOM such as the train-placement sensitivity and the fixed train order. Furthermore, the explicit consideration of demand structures allows for a bottleneck analysis by relating traffic demand and the infrastructural supply. Our model for assessing railway networks capacity can support railway practitioners for preparing and supporting the path towards the ambitious goal of sustainable traffic in Europe - with rails as its steel backbone.

■ WE-13

Wednesday, 16:30-18:00 - 20.30 SR -1.025

Modeling languages and platforms

Stream: Software Applications and Modeling Systems
Invited session

Chair: *Susanne Heipcke*

1 - Advanced programming features of Mosel 6

Susanne Heipcke, Yves Colombani

20 years after its first commercial release, the Xpress Mosel software keeps evolving according to user requirements, usage patterns and technological advances. Mosel was initially designed as an optimization modelling language that also provides programming features, its open, modular architecture allowing developers to add new functionality according to their needs. The increasing use of Mosel as general-purpose programming language was recognized by turning it into free software a few years ago. The recently released Mosel 6 further builds out its programming capabilities, addressing advanced programming needs of large software development projects. This talk discusses examples of use cases such as: (1) inspection of and interaction with external data sources or other Mosel models without prior knowledge of data types or structure: reading and storing input data of unknown type, retrieving data schema information; (2) easier integration of user inputs made via UIs, matching high-level information to model entities; (3) creation of automated testing systems with generic reporting and assertion tools, and involving inspection of the currently executing program itself. The presented examples make use of major new concepts introduced in Mosel 6, including unions (container capable of holding an object of arbitrary type/structure), subroutine references, untyped lists, and support for reflection. We also show how various other new programming features can be used to simplify existing programs. Other updates include new debugging features, new system functionality, improved handling of JSON format files, and extensions to the moseldoc tool.

2 - Modeling and Solving Optimization Problems with SAS

Philipp Christophel

In this talk we present the SAS MILP modeling environment and optimization solvers using practical examples. We discuss logical implications and automatic linearization as well the latest performance improvements for the linear and mixed-integer optimization solvers.

3 - Model Deployment in GAMS

Robin Schuchmann, Matthes Koch

In most cases, using GAMS in the typical fashion - i.e. defining and solving models and evaluating the results within the given interfaces is a sufficient way to deploy optimization models. The underlying field of mathematical optimization, in which the focus is not so much on visualization as on the problem structure itself, has remained a kind of niche market to this day. In the large and very extensive segment of business analytics, however, intuitive deployment and visualization is indispensable. Since these two areas increasingly overlap, the way optimization software is used has also changed significantly. Whereas applications used to be invoked via the command line on a local computer, today many users want to log into an online service and perform their optimization on a centralized compute resource. In this talk, real-life examples are used to show what modern software solutions with GAMS can look like. We present how to turn a GAMS model into an interactive web application in just a few steps. In addition, the generation, organization, and sensitivity analysis of multiple scenarios of an optimization model is addressed. We demonstrate how a model written in GAMS can be deployed with this application on either a local machine or a remote server. While data manipulation and visualization as well as scenario management can be done via the web interface, the model itself is not changed. Therefore, the Operations Research analyst can keep focusing on the optimization problem while end users have a powerful tool to work with the data in a structured way and interactively explore the results.

4 - The OR toolkit for practitioners - Supply Chain Apps

Jan Sigmund

The all-in-one Supply Chain Planning & Visualization solution to transform data into insights. Supply Chain Add-in extends Microsoft Excel with easy to use visualization, simulation and optimization apps.

What can you do with Supply Chain Add-in?

* Create, style, save and share beautiful data-driven maps * Accurate forward and reverse geocoding for locations worldwide * Batch distance calculation on street level worldwide * Reachability analysis with isochrones * Center of Gravity analysis to calculate the optimal number and locations of warehouses * Network Design Optimization to calculate optimal warehouse locations and good flows * Optimize pickup and delivery routes for last mile distribution * Demand forecasting for SKU's based on latest Machine Learning technology * Plan and visualize warehouse layouts and assign product groups to optimal warehouse areas.

Supply Chain Apps is used by more than 11000 Supply Chain professionals. There is also a free academic version available.

■ WE-14

Wednesday, 16:30-18:00 - 10.50 Raum 702

OR in the Global South

Stream: OR in Developing Countries
Invited session

Chair: *Philipp Trotter*
Chair: *Gerhard-Wilhelm Weber*

1 - Colored matching problems in the routing of motorcycles for vaccine distribution in rural Uganda

Corinna Mathwieser, Christina Büsing, Philipp Trotter

Providing vaccines is a critical component of quality health care. As vaccine distribution is a highly relevant topic, many concepts and models for the corresponding logistics exist. However, common concepts for the logistics of vaccine supply are often not suitable to model the situation in the Global South as they rely on fundamental assumptions concerning existing infrastructure which often do not hold true for rural areas of developing countries. The need for addressing these discrepancies becomes even more evident when considering vaccination rates, e.g. for Covid-19 (fully vaccinated: 75 % in Germany vs. 21% in Uganda, April 2022) or for diphtheria, pertussis and tetanus (immunization of children: 95 % in the European Union vs. 73 % in Sub-Saharan Africa, 2019). Moreover, many of these challenges including travel time, coverage and reachability are fortified by the fact that health care infrastructure is usually designed to be stationary, i.e. patients need to travel in order to seek vaccination at a hospital or a

doctor's office. Thus, a more mobile approach helps to make vaccines accessible in rural areas. In this talk, we consider the last mile distribution of vaccines via motorcycles with integrated refrigerators in rural Uganda. We assume a setting where vaccines are stored at health centres and need to be transported to surrounding villages and towns via motorcycle. The focus of this talk will be on the optimization of the routing of the motorcycles and its combinatorial aspects. We will introduce different matching problems on edge colored graphs, discuss their complexity and discuss how these matching problems can be used to model the planning of routes.

2 - Kerkenes Eco-Center Project in Anatolia and the future chances by OR
Gerhard-Wilhelm Weber, Francoise Summers

The Kerkenes Eco-Center Project was initiated in 2002 by Geoffrey and Françoise Summers from METU, Ankara, Turkey, 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 is to halt, and even reverse, migration from rural areas to urban centers. Advocating an environmentally friendly approach to the development and improvement of rural settlements, the project works closely with SAH-DER (The Sahmuratli Village and Kerkenes Association for Public Relations, Prosperity, Help and Support), which was established in 2003 to promote the welfare of the village of Kerkenes (Yozgat, Anatolia).

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.

In this presentation we discuss about ways how Operational Research could further contribute to the Kerkenes Eco-Center Project and, thus, to the living conditions of the people in Turkey's rural countryside and in other parts of the world.

3 - A comparative study of maintenance efficiency across public bus companies in India using DEA
Shivam Kushwaha, Shankar Prawesh, Anand Venkatesh

The maintenance departments of bus companies play a pivotal role in their overall performance. While maintenance is often seen as a support function, its various nuances and idiosyncrasies in the production process are overlooked. Effective operations and marketing cannot often overcome lacunae in maintenance practices. On the contrary, inadequate maintenance practices result in buses being off-road thereby proving to be detrimental for operations and the overall competitiveness of bus companies. In this paper, we evaluate the production performance across maintenance departments of public bus companies in India. The technique used to measure the production efficiency of maintenance departments is Data Envelopment Analysis (DEA). We have contextualized our DEA model and the associated variables to capture the production performance of maintenance departments of bus companies. The input-output data for maintenance efficiency computation is analyzed for the five years, 2013-2017. The main objective of this research study is to identify the maximum number of buses of the respective bus company which can be operated and subsequently, the achievable Fleet Utilization (FU). This study would help decision-makers understand the relative efficacy of their maintenance practices and envisage improvements therein.

■ WE-15

Wednesday, 16:30-18:00 - 10.50 HS 101

Discrete Optimization Problems III

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Oliver Stein*

1 - A Two-Dimensional Convex Shapes Bin Packing Problem in the Production of Laminated Safety Glass
Steffen Goebbels, Thomas Lühring, Jochen Rethmann

A two-dimensional nesting problem is discussed. The problem is motivated by the production of differently shaped tiles of laminated safety glass that can be represented by primitive, convex polygons. Within as few rectangular bins as possible, representing the space of a furnace, tiles consisting of two or more layers of glass with intermediate foils must be placed without overlapping. While the primary problem is to minimize the number of occupied bins, there is a new distance restriction that is specific to the given application. Distances between each tile and adjacent tiles or an adjacent furnace boundary must be neither too small nor too large to ensure the stability of the furnace filling during a lamination process. To fulfill this condition, a minimum number of additional rectangular support plates must be added. These plates are considered equivalent to tiles when measuring distances. This is a new aspect that, to our knowledge, has not been covered in the literature so far. We represent the problem as a mixed integer linear program based on no-fit polygons. For practical application, however, we compare results with those of a greedy-type heuristic.

2 - A Fast Asymptotic Heuristic for the Two-Dimensional Bin Packing Problem
Torsten Buchwald, Guntram Scheithauer

We present new results for the two-dimensional bin packing problem. We show how the First-Fit Decreasing-Height (FFDH) heuristic for the two-dimensional strip packing problem can be adapted to the two-dimensional bin packing problem. Using this adapted heuristic we derive sufficient conditions which ensure that a set of items can be packed into a single bin. These conditions are used to create a new asymptotic algorithm for the two-dimensional bin packing problem. The idea of this algorithm is based on a paper of Epstein and van Stee, who presented an algorithm with asymptotic performance of 2.25. The new sufficient conditions enable us to create a new asymptotic algorithm having an asymptotic performance ratio of 2 and running time O(n log n).

3 - Optimal configurations for modular systems
Maren Beck, Oliver Stein

The aim of this paper is to optimize modular systems which cover the construction of products that can be assembled on a modular basis. Increasing the number of different variants of individual components on the one hand decreases the cost of oversizing the assembled product, while on the other hand the cost for maintaining the modular system increases. For the minimization of the overall cost a mixed-integer optimization problem is derived. The problem cannot simply be passed to a solver for mixed-integer optimization problems, since certain dependency structures of the variables occur by which in the beginning it is not even clear how many decision variables the problem has. The problem could be reformulated into a two-level problem that takes the dependency structure into account. For such problems, decomposition methods or methods from bilevel optimization are well known. In this work, however, a different solution approach is proposed, which uses binary variables to transform the problem into a mixed-integer single-level problem, for which well-known solvers can be used. In a numerical study, this formulation is investigated using the example of a modular system for crane bridges, and it is shown that the problem formulation as a single-level problem possesses potential also for the optimization of other modular systems.

4 - Branch-and-bound for bi-objective mixed integer programming
Oryan Rampon, Sophie Parragh, Fabien Tricoire

In bi-objective mixed integer optimization, the Pareto frontier can be composed of closed, open, half-open line segments or even isolated points. In this work, we generalize an existing branch-and-bound algorithm designed for bi-objective integer linear programming to bi-objective mixed integer linear programming. We show that some of its key ingredients like filtering and branching can easily be adapted to the mixed integer case. Furthermore, we integrate several recently proposed enhancements such as presolving and probing and we propose to use the fact that each objective space point corresponding to a solution from the decision space may have multiple different inverse images in the decision space, which will allow us to compare their variables and potentially allowing us to discard non-interesting areas of the objective space. The proposed algorithm is tested on instances from the literature and compared to other recently proposed exact methods for bi-objective mixed integer programming.

■ WE-16

Wednesday, 16:30-18:00 - 20.30 SR -1.012

Simulation and Machine Learning

Stream: Simulation
Invited session
Chair: *Maximilian Moll*
Chair: *Max Krueger*

1 - Monte Carlo based Machine Learning

Sara Shashaani, Kimia Vahdat

Even though simulation is mainly used for computer models with inexact outputs, there are also direct benefits in viewing results from samples of an existing dataset as replications of a stochastic simulation. We propose solving Machine Learning (ML) prediction models with Monte Carlo (MC) approach. This allows not only more straightforward accountability for the underlying distribution of the data and more comprehensive probabilistic properties of the model but also the inclusion of the uncertainty in the input data when building the models. We opt for nonparametric input uncertainty with multi-level bootstrapping to make the framework applicable for large datasets. We argue that with innovative designs of bootstrapping and integrating variance reduction strategies, the cost of Monte Carlo (MC) based model construction is controllable. Still, the benefit is substantial in providing more robustness in the predictions. These benefits are demonstrated in several actual and simulated datasets under various structural assumptions in the data. We discuss the proposed objective function estimator's statistical properties and prove the asymptotic efficiency of the overall framework for optimization with finite data. Implementations in feature selection, which can be viewed as a particular case of hyper-parameter tuning problem, further indicate the superiority of the proposed MC-based-ML in robustness and accuracy compared to the state-of-the-art methods.

2 - Investigating bidding strategies for energy storage facilities using reinforcement learning

Nick Harder, Ramiz Qussous, Anke Weidlich

In this work, we investigate reinforcement learning to derive bidding strategies for energy storage facilities acting on electricity markets. Such strategies play a crucial role in electricity market simulation models, which can be used for different case studies, such as forecasting electricity prices in future energy scenarios with a high share of renewables. In simple power market simulation models, bidding strategies are fixed by the modeler, and are therefore not adaptive to changing market environments. Alternatively, the bidding strategies can be derived using optimization algorithms, which may result in poor performance when price uncertainty due to forecast errors is present. Reinforcement learning can both adapt the bidding strategies to changing market environments and account for the stochastic nature of the market. The scope of this work is to compare three types of bidding strategies for storage units, i.e., fixed, optimization-based and reinforcement learning-based strategies. In the first part, we compare the profits generated by single storage facilities in an energy-only market. Additionally, we introduce different degrees of forecast error to study its effect on generated profits. In the second part, we use Germany's current fleet of pumped hydropower storage parameters and compare the aggregated simulated profiles of energy storage facilities and the electricity prices to historical data. We use two scenarios representing the current and future energy systems for both parts. Analyzing the individual profits in part one along with the aggregated profiles and electricity prices in part two allows choosing the best approach for deriving bidding strategies for different research applications.

3 - Do artificial agents reproduce human strategies in the Advisers' Game?

Maximilian Moll, Jurgis Karpus, Bahador Bahrami

In the advisor game, a client has to make and update decisions about choosing which one of two advisors they should trust. Experiments have shown that human advisors can learn to play strategically instead of honestly to exploit client behavior. Here, we will analyze when and under which conditions agents trained with Q-learning can adopt similar strategies. To this end, the agent is trained against different heuristics, itself, and independently learning agents. To increase experimentation speed, an empirically tested formula is used to choose between the two competing algorithmic advisers on behalf of the human client.

4 - Iterated Boxed Pigs Game: a Reinforcement Learning Approach

Rudy Milani, Maximilian Moll, Stefan Wolfgang Pickl

This paper analyzes the iterated version of the well-known Boxed Pigs game through Reinforcement Learning. In this scenario, two pigs are restricted in a box and they have to maximize the food that they eat by pressing a lever or waiting. In our iterated version, these pigs play this game repeatedly using different strategies. We carry out two experiments: in the first one, we train two Q-learning agents against each other to see which equilibrium will be generated. In the second one, we pit the Reinforcement Learning agent against a fixed policy pig. The results of this experiment confirm the quality of Reinforcement Learning techniques in finding the best strategy for maximizing own food consumption independently from the other pig choices.

■ WE-17

Wednesday, 16:30-18:00 - 20.30 SR -1.011

Machine Learning and Data-Driven Approaches

Stream: Health Care Management
Invited session
Chair: *Marlin Wolf Ulmer*

1 - A retrospective evaluation of score-based ex-post triage policies during the COVID-19 pandemic: Simulation study by real-world intensive care data

Christina Bartenschlager

Background During the COVID-19 pandemic, authorities set up lockdown measures and infection-prevention strategies to avoid an overburdened health care system. In this context, a question on ex-post triage of intensive care patients arises. Ex-post triage is a rather young research area, which is dealt with primarily from a theoretical, ethical, and legal rather than from a quantitative perspective. Methods We focus this gap and provide quantitative analyses of score- and non-score-based ex-post triage policies using simulation and real-world electronic health record data in a COVID-19 setting. 10 different triage policies are compared by the mortality on ICU as indicator and Analyses of Variance including post hoc hypothesis tests. Results Our study shows that score-based ex-post triage policies perform superior compared to non-score-based ex-post triage. Based on our simulation model, a SAPS-score based ex-post triage is optimal and reduces mortality on ICU, depending on the scenario, by up to 18 percentage points. The longer the queue of critical care patients waiting for ICU treatment and the larger the maximum number of patients subject to ex-post triage, the greater the effect on the reduction of the mortality on ICU. Conclusion Although ex-post triage is to be understood as ultima ratio and, first, all political and health care measures are to be taken, a SAPS score-based ex-post triage policy applied in a reasonable time horizon is optimal in our simulation model. An interdisciplinary discussion including an ethical, and legal perspective is important for the social interpretation of our quantitative results.

2 - Beyond the average: An alternative to Federated Averaging in Federated Machine Learning-based digital COVID-19 diagnosis under consideration of missing data

Elion Shala, Jens Brunner, Christina Bartenschlager

All over the world, the COVID-19 pandemic has posed numerous challenges to healthcare institutions such as hospitals. Efficient and confidential diagnosis of COVID-19 patients represents a major challenge in this regard, which has given rise to the application of machine learning (ML) techniques. It has been recently shown that the collaboration of different health care institutions is beneficial, as the effectiveness of ML models is related to the amount and variety of available data. In this context, data privacy concerns arise since, by the collaboration of hospitals on ML models, sensitive patient information is to be included. For this reason, the concept of Federated Learning was proposed by Google in 2016, avoiding transporting data across different institutions. Instead, the communication between the institutions is such that local ML models are trained based on local data and the resulting local model parameters are sent to a central server, which aggregates the local results in the form of a global model. Federated Averaging provides a well-known technique, for the aggregation of local

model parameters by averaging. In this work, we propose an alternative to Federated Averaging for digital COVID-19 diagnosis under special consideration of missing data, a well-known challenge in medical applications and digital COVID-19 diagnosis. Our modified federated version of Stochastic Reduced Variance Gradient (FSVRG), namely the mFSVRG, demonstrates a more robust behavior when it comes to replacing missing data for our real-world data of different health care institutions.

3 - DENLU and leaky stanh: new activations in Machine Learning with healthcare applications in binary classification

Milena Grieger, Christina Bartenschlager

In healthcare settings, binary classification of patients is frequently applied. For example, decision-makers in hospitals seek to classify patients regarding a positive or negative diagnosis, in- or outpatients and ward, or intensive care, respectively. Lately and probably fueled by the COVID-19 pandemic, the importance of Machine Learning algorithms as decision support tools for classification of patients significantly increases in literature. While the variety of Machine Learning applications increases, there exists only a very limited number of activation functions, e.g. the sigmoid or tanh function, available for incorporation in the algorithms. We develop new activation functions, namely DENLU and leaky stanh, with applications in binary classification of healthcare data. The performance of the new activations is tested and compared with existing activations for simulated and real-world healthcare data. The latter includes three different data sets on COVID-19 diagnosis based on laboratory parameters, classification of COVID-19 patients in the emergency department regarding intensive care treatment, and classification of elective patients regarding intensive care treatment after surgery. Our analyses show, among others, that the performance of the Machine Learning model based on the new activations is comparable or superior to existing activations in many metrics, while from a theoretical perspective DENLU and leaky stanh show interesting properties with respect to S-shape flexibility and the avoidance of the problem of vanishing gradients.

4 - Data-Driven treatment policies for Dialysis patients

Manoj Kumar, Deepa Usulumarty, Ravi Brambhatt, Viswanath Billa, Narayan Rangaraj, Santosh Noronha

This research deals with some issues in managing the process of dialysis for patients who suffer from kidney failure. Selection of different treatment options and the choice of parameters within treatments are important to do based on up-to-date data. We use a quality of life parameter together with survival analysis to quantify data-driven treatment policies to manage the various stages of dialysis. Our study considers managing different treatment options for vascular access (appropriate blood vessels) during dialysis, namely arteriovenous fistula, temporary catheter and permanent catheter, and sequential deployment.

We have also tackled the problem of choice of hand for placement of the first fistula, a particular construction of an arterio-venous artificial blood vessel, which is currently the most preferred access mechanism for long-term dialysis. The data analysis of our study (319 patients at Apex Kidney Care, Mumbai, India) shows that the non-dominant hand should be prioritized over the dominant hand and that the non-dominant hand distal location should be preferred for the first fistula, followed by a second fistula at the upper arm on the same hand. The quality of life weights is computed from two different surveys considering different aspects of daily life. The survival analysis is done using univariate parametric (Weibull, exponential, etc.) and non-parametric survival functions such as the Kaplan Meier estimate. The Cox proportional hazard model is used to compute the patient-specific survival functions. We support our decision with statistical tests such as the log-rank test. Our analysis helps medical professionals to provide an optimal plan for dialysis for individual patients.

■ WE-18

Wednesday, 16:30-18:00 - 20.30 SR -1.013

Container transportation and train marshalling

Stream: Logistics
Invited session
Chair: *Nicolas Rückert*

1 - Optimization of Container Transportation in Port Hinterland with Trucks - Approaches to Cooperation

Nicolas Rückert, Kathrin Fischer

Logistics in the hinterland of ports account for up to 80% of the total cost of the maritime logistics chain. Therefore, optimizing hinterland logistics offers large potential for using infrastructure resources more efficiently, for reducing emissions and costs, and for providing high quality hinterland services to increase competitiveness. Cooperation is one promising approach here. A mathematical model for the operative optimization of container transportation in port hinterland with trucks, considering cooperation, is presented. It is discussed how costs in hinterland container logistics with trucks can be reduced by using horizontal cooperation, i.e. by sharing customer orders, and how stable and long-term-oriented cooperation can be established. A setting is considered in which each trucking company has its own customer orders, some of which it is willing to share or pass on to others, but only at a certain price or compensation. To enable and promote stable and long-term cooperation, fairness is important; therefore, different fairness constraint groups are modelled and implemented. Moreover, different constellations of so-called "trust groups", i.e. groups within which an exchange of orders may take place, are studied. The effects of cooperation under these different conditions are quantified, compared and analyzed. The analysis shows that different degrees of cooperation, i.e. different sizes of trust groups and different intensity of order exchange, as well as different fairness constraints have a strong and varying impact on the efficiency of the system, e.g. in terms of cost and emission reduction as well as with respect to the distribution of orders and profits among the trucking companies.

2 - Exploring Approaches to Integrate Scheduling Problems in Container Terminals

Teresa Marquardt, Catherine Cleophas

Large parts of the global supply chains rely on container shipping. To avoid bottlenecks, new efficient and effective approaches to harbor logistics are needed. The operations within a port's container terminal are mutually dependent. E.g., the availability of transport equipment impacts the operations of quay cranes and yard cranes. When optimizing one issue without considering others, the terminal's overall efficiency might suffer. Therefore, we optimize problems in a deeply integrated fashion. In particular, we consider the quay crane scheduling, the vehicle dispatching, and the yard crane scheduling problems. Further, unforeseen events may cause disturbances in a real-world system. E.g., congestions triggering delayed transport equipment impact subsequent operations in a domino effect, leading to sub-optimal schedules. We apply online optimization techniques to tackle this issue: The problem is solved multiple times across the time horizon. Due to the continuous updates of the database, systematic tracing of experiences, and complementary simulation experiments, reinforced learning methods are applicable in this domain. By considering only parts of the time horizon at once, we create a computationally efficient rolling-horizon strategy. The optimization approach is implemented in a Digital Twin (DT). The DT is a valid live representation of the real-world system and is suitable for simulating future scenarios. I.e., the DT creates schedules by using optimization techniques and simulates multiple runs with random components to obtain the best, robust solution. Subsequently, the DT can autonomously communicate the solution to affected agents.

3 - A Rolling Horizon Model for Sorting Schemes and their Environmental Impacts in Marshalling Yards

Max Zien, Thomas Kirschstein

Marshalling yards are nodes in rail networks where outgoing trains are built by sorting railcars of incoming trains. At those yards, greenhouse gas emissions are produced as often diesel-powered shunting locomotives are used for sorting railcars. To reduce greenhouse gas emissions, railcars should be moved as few as possible while outgoing trains must be composed. For planning the sorting process, established sorting heuristics are available. In this talk the most relevant sorting heuristics are analysed in a rolling horizon model w.r.t. their implied greenhouse emissions, i.e. incoming trains arrive at the marshalling yard in different periods of time and in each period railcars can be shunted to their designated outgoing trains or wait for shunting in later periods. For each sorting heuristic, we analyse the effect of different parameter settings (like number and composition of incoming/outgoing trains) on the total emission of the sorting process by means of a static simulation model. The results show that greenhouse gas emissions in shunting yards can be reduced by selecting a sorting heuristic based on the characteristics of the incoming and outgoing trains.

4 - A Generalized Approach for Train Marshalling
Elias Dahlhaus

The sorting requirements of freight train cars on a hump yard are specified by so called directed P-Q-trees. The leaves are the cars. The children of P-nodes can be ordered in any how. The children of Q-nodes are in fixed order. Any ordering of the leaves induced an admissable ordering of the children of any inner node is considered as an admissable ordering of the leaves. It will be argued why directed P-Q-trees are an appropriate modelling of the sorting requirements. Furthermore, the dynamic programming approach of the algorithm of Falsafain and Tamannaei to minimize the number of tracks for a one step hump yard sorting can be extended to directed P-Q-trees. In the original paper, Falsafain and Tamannaei consider only the case that the cars should be sorted in such a way that groups of cars appear consecutively. Finally, the heuristics of Dörpinghaus and Schrader is modified such that it can be integrated into the algorithm.

■ WE-19

Wednesday, 16:30-18:00 - 20.30 SR 0.019

Forecasting

Stream: Analytics and Learning
Invited session
Chair: *Sven F. Crone*

1 - Predicting Sales with Temporal Fusion Transformers
Nicki Lena Kämpf

The prediction of sales is a crucial task for the overall business planning, the cash flow management and in terms of goods also the supply chain management. In order to forecast the sales precisely, a model is needed that can identify the relevant features, deal with both continuous and categorical features and learn seasonal and long-term dependencies. One promising approach is the Temporal Fusion Transformer (TFT) architecture that combines the aforementioned qualities. Moreover, the TFT is an inherently interpretable architecture. This makes it particularly interesting for business applications since the results can be compared to the business understanding. The TFT has shown promising results for different time-series forecasting tasks including electricity consumption, stock prices as well as grocery sales. Motivated by the state-of-the-art results, this study applies the TFT to other sales data to examine their performance for other industries.

2 - Demand Forecasting: Deep, Multivariate, and Practical - Exploring the development, implementation and utilization of a retail demand forecasting support system.
Leif Feddersen, Catherine Cleophas

Retail food spoilage is both costly and ecologically and socially reprehensible. It results from retailers' attempts to provide continuously full shelves to customers in light of asymmetric costs of over- and understock, short shelf-lives of high-quality fresh products, and inaccurate forecasts.

We consider approaches to improving forecasts for the case of a large retailer with in-house production that currently undergoes significant digitalization efforts. We evaluate various forecasting techniques (smoothing methods, Prophet, LightGBM, and neural network architectures) in terms of their accuracy and business practicability. Here, we define practicability to cover computational feasibility, robustness to imperfect data, but also interpretability and acceptance. We examine the latter via structured interviews and by analyzing under which conditions managers override the model's recommendation.

Our research provides a technical perspective on the amenability of retail demand forecasting to various forecasting techniques and covariates. It also reports on the organizational challenges of implementing and utilizing forecasting systems considering theory and empirical findings in judgmental forecasting research such as algorithm aversion, double counting, and noise modeling.

Our work aims to provide a practical contribution by guiding the retail digitalization process and to provide a theoretical contribution by exploring new hypotheses in the realm of judgmental forecasting.

3 - Graph Based Time Series Analysis
Tobias Hofmann, Christoph Helmberg

The goal of this talk is to discuss graph-based mathematical methods to identify events in high-dimensional time series. We propose a general methodology that is useful for a variety of time series data. For example, we analyze data from autonomous driving experiments where we want to predict the comfort level of the passengers based on numerous physiological and technical parameters. In another collaboration, we investigate human movement data to determine motion states and occurring anomalies.

In all these applications, we aim to learn functional relationships based on high-dimensional input data. For this task, we propose discrete graph-based methods for building a finite state transition model. This allows the application of graph signal interpolation or graph-based clustering methods. Since our state transition model encodes both spatial and temporal aspects, the proposed methods have advantages when we are interested in specific sequential aspects or when underlying data is linked to some network structure.

4 - Forecasting with Neural Network Ensembles - controlling diversity through weight initialization
Sven F. Crone

Artificial neural networks require the random initialisation of parameter weights to break symmetrie and facilitate adjustment of weights through learning by gradient descent, and thus "learning". A variety of weight initialisation methods have been proposed in literature, from simple uniform random sampling across different (small) ranges of weight values (see, e.g. Sarle, 1990) to more intuitive uniform distributions (Hill et al, 2000), to sophisticated approaches by Nguyen-Widrow, and LeCunn. However, the majority of initialization methodologies developed in the 1990s were aimed at the reduction of training time and/or the convergence of a single network topology towards a suitable minimum, but largely ignored issues of out-of-sample accuracy or diversity in ensembles. To date, no studies were conducted dedicated on how to set initial weights to (a) create improved out-of-sample predictions of single network topologies, or (b) create diverse neural networks destined for ensembles, which require diversity to achieve robust ensembles which increase accuracy and reduce variance of predictors. Our experiments on a large real-world dataset employing multiple step-ahead errors show that the setting multiple initializations wisely will impact accuracy, robustness of accuracy, and runtime as well, determining the operational efficacy of the models in use.

■ WE-20

Wednesday, 16:30-18:00 - 20.30 SR 0.016

Behavior and Dynamics

Stream: Game Theory and Behavioral Management Science
Invited session
Chair: *Guido Voigt*

1 - Split-Award Auctions and Supply Disruptions
Nicolas Fugger

We consider a buyer facing several potential suppliers that might fail to deliver. The buyer conducts a procurement auction to determine one or more contract suppliers and a price. If all contract suppliers fail to deliver, the buyer tries to source from non-contract suppliers.

The mitigation of supply risks plays an important role in procurement practice but attracted little attention in the academic analysis of procurement auctions. Academic research on multi-sourcing procurement auctions typically analyzes these auctions as stand-alone events. In contrast, we investigate the influence of the auction design on the post-auction market structure and identify an effect favoring multi-sourcing. The insights provide procurement managers guidance for their sourcing decisions.

We apply game-theoretical methods to analyze a stylized model in which a cost-minimizing buyer needs to source from profit-maximizing suppliers who might fail to deliver.

First, we show that in such a setting, multi-sourcing does not only reduce the supply risk but might also yield lower prices than single-sourcing. The sourcing decision affects the post-auction market structure such that being a non-contract supplier becomes less attractive in

the case of multi-sourcing. Second, if suppliers are heterogeneous regarding their disruption probabilities, less reliable suppliers will bid more aggressively than more reliable competitors causing an adverse selection problem. Furthermore, we show that attracting an additional supplier can be risky, increasing the auction price and the buyer's total expenses.

Our analysis reveals a pro-competitive effect of multi-sourcing. The effect is especially important if the buyer's value for the item is substantially larger than suppliers' production costs.

2 - Consumer Behavior Towards Different Carbon Footprint Reductions

Guido Voigt

Carbon emissions reduction initiatives have received considerable attention at the corporate level. Companies such as Daimler, Apple and Amazon have publicly declared their goal of becoming carbon neutral, or "net zero" in a near future. They are responding to a growing demand for sustainable products and services. Companies have a variety of options for carbon emission reductions available to them, including internal reductions such as adopting renewable energy, as well as buying carbon offsets. This raises the question of whether consumers perceive the different types of carbon emission reductions as equivalent, or whether they favor the implementation of internal measures. We investigate this issue empirically for the shipment of parcels through surveys and incentive-compatible discrete choice experiments. We find clear consumer preferences and willingness to pay for companies to reduce their carbon footprint. These are particularly strong when companies internally reduce their controllable emissions rather than buying carbon offsets, and it is especially true for eco-conscious consumers.

3 - Time vs. Money Trade-offs: laboratory experiments

Johanna Dujesiefken

We present laboratory experiments to better understand how time investment behavior and monetary investment behavior differ in dynamic environments. In contrast to earlier research that relies on static surveys and hypothetical decisions, we analyze two incentivized experimental tasks in which monetary investments and time investments only differ in their framing. In the first experimental task, subjects have a budget of a resource (time or money) for a current task. In this scenario, investment decisions limit the amount of productive time/work on the current task. In the second experimental task, subjects' investment decisions do not limit the amount of productive time/work on the current task, but available resources for later, unspecified tasks. Contrary to the normative prediction that the framing of the resource (time/money) should not matter, we observe that time budgets for current tasks lead to earlier and less too late investments that are closer to the normative prediction, while monetary budgets don't. In turn, when investments only affect future budgets, neither monetary budgets nor time budgets nudge the favorable "first investing, then harvesting" structure.

4 - Decreasing viability in tychastic controlled systems

Sigifredo Laengle, Tomás Laengle Aliaga

The viability kernel in Viability Theory depends on control variables and usually also on uncontrolled ones. Control variables try to increase viability, and uncontrolled ones instead destroy it. Thyches are uncertainties without statistical regularity that diminish viability. We progress in the study of both effects. We propose a version of the Viability Theorem and specialise it by introducing the sets constructor and the destructor of viability. Next, we show a convergent algorithm that contains a Minkowski difference between both sets. We also find such difference interprets the problem adequately.

■ WE-21

Wednesday, 16:30-18:00 - 30.96 Seminarraum 1. OG (R104)

Shop Scheduling and Workforce Scheduling

Stream: Project Management and Scheduling
Invited session
Chair: *Tristan Becker*

1 - Propagation and branching strategies for job shop scheduling minimizing weighted energy consumption

Andreas Linß, Andreas Bley

We consider a job shop scheduling problem with time windows, flexible energy prices, and machines whose energy consumption depends on their operational state (offline, ramp-up, setup, processing, standby or ramp-down). The goal is to find a valid schedule that minimizes the overall energy cost. To solve this problem, we developed a branch-and-price-and-cut algorithm based on a time indexed ILP formulation, which uses binary variables that describe blocks spanning multiple inactive periods on the machines.

In this presentation, we discuss the propagation and branching schemes used in this algorithm. These strategies, which are specifically tailored for energy related machine scheduling problems, primarily aim to determine and sharpen the activity profiles of the machines (and thus reduce the number of the inactive block variables) and address the workload profile of the tasks with lower priority. Computational experiments validate the efficiency of these techniques.

2 - A multi-method approach to scheduling and efficiency analysis in dual-resource constrained job shops with processing time uncertainty

Fabian Dunke, Stefan Nickel

In dual-resource constrained job shop scheduling, jobs have to be assigned to workers and machines. While the problem is notoriously hard in terms of computational complexity, additional practical difficulties arise from data uncertainty and worker efficiency variation. In this paper, we propose a methodological pipeline combining mathematical optimization, simulation, and data analysis to cope with these aspects over time. Accounting for uncertain worker processing times, we employ an iterative two-stage optimization-simulation approach: A first-stage optimization model determines an assignment of workers to jobs; in the second stage, the scheduling of this assignment is evaluated operationally using sampled realizations of worker processing times. Both stages are executed in an alternating fashion until no further improvement is possible in the average realized makespan. At the end of a work day, realized worker efficiencies are then measured in a slacks-based data envelopment analysis on the operations level. Workers learn about their individual efficiency and are prompted to reduce inefficiencies. The resulting overall methodology not only provides robustified schedules for dual-resource constrained job shops under uncertainty, but also reduces the impact of uncertainty over time by motivating workers to operate on the efficient frontier. Computational results are conducted in several settings with both heuristic and exact solution procedures for the second-stage dual-resource constrained job shop scheduling problem. The results demonstrate the versatility of the outline with respect to addressing uncertainty and worker inefficiency.

3 - Action Space Designs for Dynamic Scheduling with Uncertain Processing and Sequence-Dependent Setup Times

Jan-Niklas Dörr, Alexander Pahr, Martin Grunow

We investigate real-time scheduling of stochastic flexible shops with sequence-dependent setup times in a practical use case. The problem can be expressed as a dynamic programming problem in which a new decision epoch is reached whenever a machine becomes idle. Accordingly, we define a Markov decision process (MDP) formulation, which serves as a generic basis for real-time scheduling. As policy approximation, we suggest dispatching rules developed by Genetic Programming (GP). In this concept, the design of the action space defines the size of the solution space and thus, the quality of the policy approximation. Hence, we develop different action space designs. To evaluate our real-time approach, we compare it to existing designs. As a static benchmark, we implement a two-stage stochastic programming approach and a deterministic approach based on expected values, both solved by constraint programming.

4 - Stochastic Rotating Workforce Scheduling Under Uncertain Staffing Requirements

Tristan Becker

Rotating Workforce Scheduling is an essential planning task in many industries. In a rotating schedule, each employee starts at a different part of the schedule, and after a specific time, the schedule repeats. The length of the schedule increases with a higher number of employees. At the same time, various constraints on work sequences and days off must be taken into account. When devising a rotating schedule, the precise number of employees needed for each day and shift is typically

uncertain, e.g., due to demand fluctuations. We model the Rotating Workforce Scheduling Problem as a two-stage stochastic optimization problem to account for the uncertain staffing requirements. The model minimizes the costs of coping with the uncertain staffing requirements. We use a scenario approach to model the staffing requirement uncertainties, applying scenario reduction to obtain a tractable set of scenarios. The first stage determines a base schedule, anticipating the uncertainties in the second stage by, e.g., hiring more employees and overstaffing. In the second stage, it is possible to recover from staff shortages using several recourse actions. However, the first-stage decisions limit the number of on-call duty activations and employee call-ins for each day and shift combination. We investigate the benefits of anticipating the uncertainty in a case study for a large number of simulated realizations of the uncertain staffing requirements by comparing the stochastic optimization approach against a deterministic approach. We find that the costs of handling the uncertainty are significantly lower when choosing a rotating schedule that anticipates the uncertainties of the staffing requirements.

■ WE-22

Wednesday, 16:30-18:00 - 20.30 SR -1.008 (UG)

Methods

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *Mayowa Ayodele*

1 - A Pre-Clustering approach to Density Peak Clustering Algorithm by Grey Wolf Optimizer

Ms. Preeti, *Kusum Deep*

Density peak clustering algorithm (DPC), which automatically recognizes the high density point and relatively large distance points as cluster centers fails to identify the correct number of cluster, and is dependent on the user defined cut-off distance dc .To overcome the problem, a clusters center initialization for DPC using Grey Wolf Optimizer (GWO) is built. The Grey wolf optimizer is well known Nature Inspired Algorithm (NIA) which is inspired by the behavior of grey wolf in nature to hunt in a cooperative way. It is easy to implement due to its simple structure, faster convergence, and an excellent performance over other NIAs. A fitness function is constructed dependent on the density and the distance of the points and is minimized using the intelligent search ability of GWO to find the optimal k cluster centers. To investigate the performance of the proposed method, experiments on the real word data and the synthetic data is performed using different clustering criteria. The extensive studies address DPC defects and achieves much better clustering results than other famous and powerful clustering methods.

2 - Solving asymmetric travelling salesman problem using artificial humming bird algorithm

Karuna Panwar, *Kusum Deep*

The Artificial Humming Bird (AHA) is a newly introduced bio-inspired algorithm that mimics hummingbirds' unique flying abilities and foraging methods. It was initially proposed to solve continuous optimization problems and report impressive results. In this study, a discrete version of AHA is presented and used to solve well known combinatorial optimization problem, the asymmetric travelling salesman problem (ATSP). As ATSP is a combinatorial optimization problem, the continuous values obtained from the basic AHA are changed to discrete values using the order based decoding method. Further, the exploration and exploitation capabilities of the proposed algorithm are improved by the symmetry operator and the 2-opt algorithm. The proposed discrete AHA (DAHA) has been evaluated over several ATSP instances, and the computational results showed that it is a promising algorithm. Also, the performance of the proposed algorithm is compared with similarly developed algorithms such as particle swarm optimization (PSO), grey wolf optimizer (GWO), whale optimizer (WOA) and sine cosine algorithm (SCA). The proposed DAHA significantly outperformed these algorithms for a majority of ATSP instances.

3 - Towards Multi-Objective QUBO Solving

Mayowa Ayodele, *Richard Allmendinger*, *Manuel López-Ibáñez*, *Matthieu Parizy*

In recent years, there has been significant research interest in solving Quadratic Unconstrained Binary Optimisation (QUBO) problems. Physics-inspired optimisation algorithms such as quantum annealing, or adaptations of simulated annealing have been proposed for deriving optimal or sub-optimal solutions to QUBOs. These methods are particularly attractive within the context of using specialised hardware such as quantum computers, application specific CMOS and other high performance computing resources for solving optimisation problems. Examples of such solvers are D-wave's Quantum Annealer, IBM's Quantum System One and Fujitsu's Digital Annealer. Combinatorial optimisation problems are therefore converted to QUBOs so that these solvers can be applied to them. Quantum and quantum-inspired optimisation algorithms have shown promising performance when applied to academic benchmarks such as travelling salesman, knapsack, quadratic assignment, and graph partitioning problems. They have also been successfully applied to real-world problems in logistics and finance. However, QUBO solvers are single objective solvers. To make them more efficient at solving problems with multiple objectives, their algorithms need to be adapted. In this work, we propose modifications to the algorithm that supports the Digital Annealer such that it can solve problems with multiple objectives more efficiently. We compare the proposed algorithm with existing methods which entails combining multiple objectives into one. We show that the proposed approach achieved better solution quality in a shorter time when compared to single-objective methods.

Thursday, 8:30-9:30

■ TA-02

Thursday, 8:30-9:30 - 30.95 Audimax A

Semi-plenary talk Kara

Stream: PC Stream
Semi-plenary session
Chair: *Frank Schultmann*

1 - Network Design in Humanitarian Logistics
Bahar Yetis Kara

Emerging humanitarian crises of the last decades demonstrated the necessity to excel in the management of time constraints, limited resource amounts and high levels of uncertainty. Syrian refugee crisis that has been going on for more than a decade illustrates one of the main characteristics of humanitarian logistics: selectivenes. Management of scarce resources do not always allow for the coverage of all of the demand. Dynamics of location decisions and selectiveness characteristics highlight the fundamental importance of network design in humanitarian logistics. Recent outburst of COVID-19 pandemic show that quick responses to humanitarian crises is essential. The problems of fast distribution of masks, PCR tests and vaccines show that humanitarian crises are rapid changing situations where new needs and questions arise continuously. Scarcity of resources of time and supply in a crises that require quick response also obligate selectiveness in terms of the demand that can be covered. Current situation in Ukraine shows that, unfortunately, there will always be emerging humanitarian crises in the world and Network Design in Humanitarian Logistics will continue to be a critical research topic in the years to come. In this talk, a general framework for network design in humanitarian applications will be provided and examples from different applications will be discussed. The examples analyzes Turkey's experience and lessons learned over a decade to provide a road-map for possible and similar situations in the future.

■ TA-03

Thursday, 8:30-9:30 - 30.95 Audimax B

Semi-plenary talk Stützle

Stream: PC Stream
Semi-plenary session
Chair: *Veit Hagenmeyer*

1 - Automated Design of Algorithms
Thomas Stützle

The design and development algorithms can be time-consuming and difficult for a number of reasons including the complexity of the problems being tackled, the large number of degrees of freedom when designing an algorithm and setting its numerical parameters, and the difficulties of algorithm analysis due to heuristic biases and stochasticity. Still very often this design is done manually, mainly guided by the expertise and intuition of the algorithm designer. However, the advancement of automatic algorithm configuration methods offers new possibilities to make this process more automatic, avoid some methodological issues, and at the same time improve the performance of algorithms.

In this talk, I will highlight the advantages of addressing algorithm design and configuration by algorithmic techniques; describe the main existing automated algorithm design techniques; and discuss some of the main successful applications of automated design we have in our own work. In particular, I will show how flexible algorithm frameworks can support the automated design of high-performing hybrid stochastic local search algorithms. In fact, even for problems that have received very high attention in the literature new state-of-the-art algorithms can be obtained automatically, that is, without manual algorithm tuning. I will conclude arguing that automated algorithm design will also have the power to transform the way algorithms for difficult problems are designed in the future.

■ TA-04

Thursday, 8:30-9:30 - 10.11 Hertz-Hörsaal

Semi-plenary GOR Company Award

Stream: PC Stream
Semi-plenary session
Chair: *Alf Kimms*

Thursday, 10:00-11:30

■ TB-04

Thursday, 10:00-11:30 - 10.11 Hertz-Hörsaal

GOR Master Thesis Awards

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

1 - A Two-Stage Stochastic Optimisation Model for Urban Same Day Delivery with Micro Hubs
Charlotte Ackva

An increasing number of local shops offer fast local delivery to compete with the online giants. However, the distribution of parcels from shops to customers is often lacking consolidation opportunities. Thus, shops start collaborating on urban delivery by using shared vehicles for consolidated transportation of parcels. The shared vehicles conduct consistent daily routes between stations in the city, which serve as transhipment and consolidation centres. This allows stores to bring orders to the next station, where the parcel is picked up by a vehicle and delivered to the station closest to its destination - if it is feasible with respect to the vehicle's consistent daily routing schedule. Creating effective schedules is therefore very important. The difficulty of finding an effective consistent route is amplified by the daily uncertainty in order placements. In this work, we model the problem as a two-stage stochastic program. On the first stage, the vehicle schedules are determined. On the second stage, the realized orders are routed. The goal is to satisfy as many orders as possible with the shared vehicles. We solve the problem by investigating the Progressive Hedging Algorithm, a scenario-based solution approach. To assess the methods' performance, we further consider the optimal solution without consistency constraints as an upper bound and a practically-inspired heuristic solution as benchmarks. We conduct a method analysis and test our approach on different instances. We find that PH behaves rather poorly on random data, but performs particularly well on highly structured demand.

2 - Solving Customer Order Scheduling Problems with an Iterated Greedy Algorithm
Julius Hoffmann

In this thesis, the customer order scheduling problem is studied for different problem configurations with iterated greedy algorithms. In contrast to classical scheduling problems, the customer order scheduling problem considers the scheduling of jobs that belong to customer orders and each order is only completed when each job of the order has finished. Through a systematic literature review, one previously studied problem configuration was chosen and two not yet investigated problem configurations were derived for further examination. Followingly, the minimization of the sum of order completion times and the minimization of the earliness-tardiness are studied in the dedicated machine environment where each order places one job on each machine. Furthermore, the minimization of the sum of order completion times in a flow shop environment is investigated. For each of the three problem configurations, theorems are presented, and multiple iterated greedy algorithms are developed. These heuristics are compared with existing solution methods in computational experiments in terms of the best solution found after a given time. The evaluation of the experiments shows that the developed algorithms lead to sufficient results for each of the different problem configurations of the customer order scheduling problem and can compete with existing solution methods.

3 - The stochastic bilevel selection problem
Jannik Irmai

We consider a bilevel continuous knapsack problem where the leader controls the capacity of the knapsack, while the follower chooses a feasible packing maximizing his own profit. The leader's aim is to optimize a linear objective function in the capacity and in the follower's solution, but with respect to item values that can be different from the follower's item values. We address a stochastic version of this problem where the follower's profits are uncertain from the leader's perspective, and only a probability distribution is known.

This problem is #P-hard for the case of independently and uniformly distributed follower profits. The main contribution of this work is the development of two pseudo-polynomial time algorithms, one for independently finitely distributed follower profits and one for independently continuously uniformly distributed follower profits. Both algorithms have a run time that is polynomial in the number of items and linear in the sum of the weights of the items, so that they are efficient if the size of the items is bounded by a constant, as is the case in the bilevel selection problem.

■ TB-05

Thursday, 10:00-11:30 - 11.10 Engelbert-Arnold-Hörsaal (EAS)

Supply Chains for Chemicals

Stream: Supply Chain Management
Invited session
Chair: *Moritz Fleischmann*
Chair: *Heiner Ackermann*

1 - Solving the Westenberger-Kallrath problem with reinforcement learning
Philipp Willms, Marcus Brandenburg

For decades, production planning and scheduling has been a major field of study for researchers and practitioners. The classical Westenberger-Kallrath (WK) problem which was published in 2002 still serves as a valid benchmark for production planning and scheduling in the chemical process industry. From a mathematical modeling and algorithmic perspective, common solution approaches in the past made use of linear programming (LP) methods or metaheuristics. Nowadays, algorithmic advances in artificial intelligence unfold new opportunities for integrated modeling and solution methods. We investigate the application of reinforcement learning (RL) to solve the WK problem. In particular, we train agents in connection with a discrete-event simulation model to schedule the production operations with the objective to minimize makespan. The agents' performance is further evaluated by comparison with heuristic approaches. We detect modeling and implementation challenges, current limitations as well as future research perspectives on the practical usage of RL for production scheduling problems with complex material flows.

2 - Decision support for S&OP coordination under asymmetric decision-making power: A case study from the agrochemical industry
Christoph Loeffel, Moritz Fleischmann, Steffen Klosterhalfen, Tobias Hausen

To serve the seasonal demand for crop protection products by farmers around the globe, agrochemical companies must operate multi-echelon, long lead time supply chains. In order to prepare for an uncertain season, integrated planning across functions is key. At the case company, cross-functional coordination is reached through annual S&OP budget meetings hosted by the business unit head together with senior management of relevant functions such as sales and supply chain. Through the budgeting process, a shared plan is developed to coordinate commercial plans of the sales department and production plans of the supply chain organization, both of which need to react to short-term market signals. Sales and supply chain therefore agree on a set of volume guarantees for the available supply throughout the planning horizon. The guarantees are subject to a maximum inventory level imposed by the business unit head. Our project focuses on the choice of these volume guarantees. Specifically, we support the iterative and unstructured negotiation process currently in place at the case company, by developing an optimization-based budget planning model. Importantly, the model reflects existing differences in decision making scope and power of the relevant actors. In addition, the model captures the available flexibility of future plan adjustments. To this end, we use an affine adjustable robust optimization (AARO) approach. In a numerical study, we empirically evaluate our model against simple benchmarks and study the solution structure of the obtained guarantee allocations.

3 - Tactical Production Planning for Uncertain Seasonal Demand
Pardis Sahraei, Moritz Fleischmann

Seasonal demand patterns force companies to pre-produce to fulfill peak-season demand in a competitive market without wasting idle resources off-season. However, market uncertainty and long production

lead times complicate corresponding production and inventory planning, since production cannot react quickly to new demand information that is gathered as the season is approaching. Production planning has to take this uncertainty into account. In this paper, we model demand uncertainty in a novel way by expressing it through seasonal rather than monthly parameters. To estimate these parameters, we cluster the products, based on relevant structural features. We then use the obtained error distributions for sampling-based tactical production and inventory planning.

4 - On a two-stage production planning problem in a pharmaceutical production network

Heiner Ackermann, Erik Diessel, Sandy Heydrich, Raphael Kühn, Maren Manzke

We introduce a production planning problem that arises in a two-stage pharmaceutical production process. In the first stage, an intermediate product of limited shelf-life is produced, which is then further processed and finally packaged in the second stage.

Because of limited production capacities, the process owner has contracted so-called contract manufacturing organizations (CMOs) to carry out the process. Each CMO is qualified to perform only one of the steps at a certain scale. Scales are either one or two, and scales are fixed. That is, it is prohibited to run a step at scale one although the CMO is qualified only for scale two, and vice versa. Moreover, each CMO for the first production step is permitted to ship intermediate product to some but not all the CMOs for the second step.

CMOs offer time slots to the process owner who then decides which slots to use und how to connect them. In doing so, the process owner considers various objectives:

- Maximize the overall output. - Minimize waste, i.e., minimize the number of slots of scale two which are connected only to one slot of scale one. - Maximize robustness, i.e., avoid connecting slots where the difference between end of the first and start of the second slot is only slightly larger than the shelf-life of the intermediate product. - Minimize mixing, i.e., the number of slots of the second stage of scale two which are connected to two different slots in the first stage.

In our talk, we describe algorithms for solving this problem: The base problem neglecting waste, robustness and mixing can be considered as a b-matching problem. For the general setting we describe an approach to compute the Pareto set of non-dominated production plans using an integer linear program as subroutine.

■ TB-06

Thursday, 10:00-11:30 - 10.91 Redtenbacher-Hörsaal

Real Options Analysis for Energy Investment Decisions

Stream: Decision Analysis and Support
Invited session

Chair: *Reinhard Madlener*

1 - Industrial Utilization or Storage of CO2? A Compound Real Options Valuation for the Retrofitting of Coal-Fired Power Plants

Reinhard Madlener, Qinghan Yu

We investigate the sequential investment in carbon capture and storage (CCS), i.e. the case of retrofitting of a coal-fired power plant, and carbon capture and utilization (CCU) for methanol production. A (nested) compound real options model based on a backward recursive dynamic programming algorithm is used for the analysis. The options to invest in CCS and CCU are investigated individually first, and then sequentially, leading to a hybrid CCUS plant that enables both methanol production and CO2 storage. The prices of electricity, carbon and methanol are considered as stochastic and correlated with each other. Managerial flexibility exists regarding a postponement of the investment decision and the real-time optimization between selling methanol to the market or storing CO2 for earning carbon credits after establishing the CCUS plant. We find that at today's relatively high CO2 prices CCS investment is economically rational, whereas CCU for methanol is not. Combining CCS with CCU increases the overall investment probability and potential for larger profits. Since methanol is more valuable than CO2, CCU can be expected to dominate the value of the compound option for the case of favorable market conditions (i.e. sufficiently high methanol and CO2 prices).

2 - A Fuzzy Real Options Analysis of Investments in Coal-Fired Power Plants Retrofitted with CCS or CCU

Qinghan Yu, Reinhard Madlener

In this paper, we evaluate the two carbon capture, utilization, and storage (CCUS) technologies available to a coal-fired power plant. Specifically, coupled with retrofitting a carbon dioxide (CO2) capture unit, the power plant owner may decide to invest either in CCS facilities for permanent storage or in a CCU plant for methanol production to maximize his/her profits in treating CO2 emissions. For the investment analysis under uncertainty, we apply the discrete-time fuzzy payoff method proposed by Stoklasa et al. (2020) to account for multiple scenarios as well as the time-to-build aspect. The latter feature arises from the fact that we assume that the investor decides to implement the project in stages, i.e., by first retrofitting a capture unit and then proceeding with the construction of transportation and storage facilities or a CCU plant, depending on how market conditions evolve during the initial construction phase. For the assumptions made, we find that CCS investments will be desirable in 2025, while investments in CCU methanol production are economically unfavorable in the current environment. However, we provide some evidence that CCU methanol production has the potential to completely overshadow CCS due to the high price of methanol.

3 - A Real Options Analysis of the Siting and Cost-Efficient Layout of Charg-ing Infrastructure for Fuel Cell and Battery Electric Vehicles

Lars Wohlan, Reinhard Madlener, Jan Martin Specht

The German government wants a total of 10 million electric cars on German roads by 2030 and is aiming for complete electrification of road traffic by 2050. Currently, the focus is particu-larly on the development of charging infrastructure for Battery Electric Vehicles (BEVs), with 1 million publicly accessible charging stations to be built by 2030. However, the expansion of hydrogen infrastructure is also being supported with large subsidies. Although there are nu-merous studies on either the cost of charging infrastructure for BEVs or fuel cell electric vehi-cles (FCEVs), there are few comparative research results available so far. In this study, there-fore, a model for the spatial distribution of charging infrastructure for BEVs and FCEVs is first developed for the district of Steinburg in Schleswig-Holstein. In a second step, the results and corresponding economic costs are compared in a real options analysis for the period 2021 to 2050, considering different expansion curves. In addition to the hardware infrastructure costs, the two cost elements O&M and electricity or hydrogen are taken into account. The re-sults of the real options analysis show that the total cost of charging infrastructure for BEVs is always lower than the cost of FCEVs, considering the defined framework conditions. Especially at low penetration rates, the total cost of charging infrastructure for FCEVs is significantly higher than for BEVs. The total costs are dominated by the cost elements electricity and hy-drogen. Furthermore, it could be shown that the production costs for hydrogen per kg would have to decrease to EUR 1.2 to EUR 1.7 for the period 2031 to 2050, so that a change of the expansion focus from BEV charging infrastructure to FCEV charging infrastructure makes sense after 2030.

4 - Evaluation of inventory policies with time-dependent purchase prices

Philipp Erfurth, Matthias Gerhard Wichmann

Goods and services are subject to severe time-dependent value fluctuations. This applies for energy resources, such as gasoline and diesel at gas stations, as well as for electricity. For instance, the feed-in of renewable energies into electricity grids is associated with time-dependent energy prices on the electricity spot market which fluctuate strongly. Therefore, in the context of the energy transition and the growing share of renewable energy, it can be assumed that price volatility is constantly increasing. For companies, this energetic evolution affects energy procurement costs. The timing and quantity of purchasing energy is the result of a complex decision-making situation, which is largely determined by the uncertain energy consumption in production and the use of energy storage systems.

Energy storage systems, like warehouses for physical goods, serve to decouple energy procurement and consumption in terms of time. However, it is still a matter of debate, if inventory policies can be used for inventory control of energy storage facilities. Because of this uncertainty a particular importance is to understand whether conventional inventory policies are able to cope with time-depending values or if smart policies may achieve economic benefits. With this background, this article examines the business implications onto energy and production management. Starting from given production schedules based on real-world production systems, energy procurement strategies are

analyzed ex-post in a scenario-based manner with Monte Carlo simulations using the programming language Python. The results show a need for research regarding further value-oriented developments of inventory policies.

■ TB-07

Thursday, 10:00-11:30 - 10.91 Grashof-Hörsaal

Quantum Computing for Decision Support

Stream: Decision Analysis and Support
Invited session
Chair: *Pascal Halffmann*

1 - Warm-starting quantum optimization

Daniel Egger, Jakub Marecek, Stefan Woerner

There is an increasing interest in quantum algorithms for problems of integer programming and combinatorial optimization. Classical solvers for such problems employ relaxations, which replace binary variables with continuous ones, for instance in the form of higher-dimensional matrix-valued problems (semidefinite programming). Under the Unique Games Conjecture, these relaxations often provide the best performance ratios available classically in polynomial time. Here, we discuss how to warm-start quantum optimization with an initial state corresponding to the solution of a relaxation of a combinatorial optimization problem and how to analyze properties of the associated quantum algorithms. This allows the quantum algorithm to inherit the performance guarantees of the classical algorithm. We illustrate this in the context of portfolio optimization, where our results indicate that warm-starting the Quantum Approximate Optimization Algorithm (QAOA) is particularly beneficial at low depth. Likewise, Recursive QAOA for MAXCUT problems shows a systematic increase in the size of the obtained cut for fully connected graphs with random weights, when Goemans-Williamson randomized rounding is utilized in a warm start. It is straightforward to apply the same ideas to other randomized-rounding schemes and optimization problems. Furthermore, we will also discuss the scaling of the QAOA on superconducting quantum computing hardware.

2 - A Quantum Computing Approach for the Unit Commitment Problem

Pascal Halffmann, Jonas Koppe, Kai Plociennik, Michael Trebing

A both stable and environmentally sustainable energy supply is vital for future-proof economic growth and social welfare. However, energy generation planning, the so-called unit commitment problem (UCP), is rather challenging due to properties of power grid and power units. This is exacerbated by the increasing reliance on renewable energy adding uncertainty to the energy supply. As energy generation is connected to a cost-sensitive and fast-moving market, there is a high incentive to find the optimal solution of UCP in short time, a task solvers on classical computers often cannot accomplish. In contrast, quantum computers may enable rapid solving of optimization problems due to quantum mechanics based computational paradigm. While only few quantum computers of limited size are currently available, this is a promising technology of the near-term future. We propose a quantum computing-oriented model of the unit commitment problem considering demand satisfaction and properties of the power units. Our modelling addresses the requirements and challenges of present quantum hardware: number of qubits, connectivity, and noisiness demand a suitable and more complex formulation. For small- and medium-sized problem instances, we test our formulation on both the quantum annealer by DWave and on a universal quantum computer by IBM. For comparison, we perform a benchmarking via a MIP formulation and a MIP solver on classical hardware. These results allow us to give a prediction if and how quantum supremacy can be achieved. Further, we discuss the possibility of integrating uncertainty of the renewable energy supply to our formulation. Since quantum computers have advantages in dealing with uncertainties, this may increase the utility of our approach.

3 - Improving quantum computation by optimized qubit routing

Friedrich Wagner, Andreas Bärmann, Frauke Liers, Markus Weissenbäck

As current quantum hardware suffers from high error rates and noise sensitivity, it is crucial for quantum algorithms that gate numbers and circuit depths are kept small.

However, typically a significant number of additional gates are inserted during the compilation of quantum algorithms onto specific hardware. Those artificial gates are added in a compilation step called qubit routing by swap insertion. Their mere purpose is to map the algorithms two qubit gates to neighboring physical qubits in the target hardware.

For this problem, we propose a fast and high-quality heuristic based on integer programming. Our approach decomposes the routing task into an allocation subproblem and a set of token swapping problems. For the allocation task, we develop a binary linear program based on recent work by Nannicini et al. ([1]). We strengthen its linear formulation by novel valid inequalities. For the token swapping part, we enhance an existing approximation algorithm ([2]).

Our numerical results show a significant reduction in the number of artificial gates and output circuit depth, when compared to various state-of-the-art heuristics. Furthermore, experiments on real hardware show improved success probability of example quantum algorithms when compiled with our routing procedure. Those results demonstrate the influence of routing on the performance of near-term quantum hardware in general, and indicate the potential of our approach.

[1] Giacomo Nannicini, Lev S Bishop, Oktay Gunluk, and Petar Jurcevic. Optimal qubit assignment and routing via integer programming, 2021.

[2] Tillmann Miltzow, Lothar Narins, Yoshio Okamoto, Günter Rote, Antonis Thomas, and Takeaki Uno. Approximation and Hardness of Token Swapping, 2016.

4 - The ride pooling problem

Michele Cattelan, Sheir Yarkoni

Many emerging commercial services are based on sharing and pooling of a given set of agents. Especially products like mobility as a service, food delivery etc. have had a great impact on society. These kinds of problems can be defined as generalizations of the Vehicle Routing Problem (VRP) and, therefore, of the Travel Salesman Problem (TSP). Here we focus on one such pooling problem, the Ride Pooling Problem (RPP), which is known to be NP-hard. At Volkswagen, we find this problem of interest not only for its connection to the automotive industry, but because, due to its flexibility, it can be used for solving a large variety of optimization problems. Due to this complexity, this problem is of interest for the field of quantum optimization as well. In the past years some quantum algorithms have shown the potential to outperform classical algorithms. Currently, the most promising algorithms are quantum annealing and the quantum approximate optimization algorithm. Both of these algorithms require problems to be formulated as quadratic unconstrained binary optimization (QUBO) problems. The connection between quantum algorithms and QUBO formulations lies in the isomorphism between QUBO problems and Ising Hamiltonians, which can be implemented natively on quantum hardware. In this work, we propose QUBO formulation of the RPP. We obtain a formulation that implements the inequalities of the model as quadratic terms and we explicitly show how to mathematically model the generalization from VRP/TSP to RPP. Similar to those, we find that the number of variables required to our model is quadratic, however we show also how to remove a small number of variables specific to RPP.

■ TB-08

Thursday, 10:00-11:30 - 10.50 HS 102

Optimal Power Flow Problems and Solution Methods I

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *John Warwicker*

1 - Optimized Congestion Management in Balancing Market for Electricity Transmission System Operator

Sinan Eren, Ali Nezih Güven

A core function of each Electricity Transmission System Operator (TSO) is the procurement of ancillary services in real time balancing markets, necessary for a stable and reliable operation of the system. In

balancing market, TSO controls active power reserves to keep system frequency and reactive power reserves for bus voltages. Apart from reserves, TSO manages congestions in transmission network in the sense of single or multiple elements overloadings or violations of the N-1 security criterion. Congestion management is achieved by rescheduling generation using mainly operators' experiences. However, TSO has legal obligations to procure ancillary services in accordance to economic, transparent, non-discriminatory procedures. This work aims to develop an algorithm / software system for TSO to decide optimum redispatch in the sense of economy and security. Algorithm is deployed as a real time running application for real life large-scale network. On this matter, integrations with network modelling database and real time balancing market (based on Turkish Balancing Market) are implemented. Problem is formulated as Optimal Power Flow problem. Objective function of the algorithm is minimization of cost of the generation shift. The security constraints will be satisfied by power flow equations. Constrains are generation active and reactive limits, line flow and bus voltage limits. Power flow equations are nonlinear and nonconvex by nature. In order to obtain robust application, linearization techniques are implemented. Compared with the commonly used DC OPF methods, reactive power and bus voltages are considered in equations. Problem is constructed as Mixed Integer Quadratically Constrained Linear Programming. Challenge is size of problem (Turkish Electricity Network).

2 - Optimal Design of Distributed Energy Systems with Complementarity Reformulations for Multiphase Optimal Power Flow
Oleksiy Klymenko, Ishanki De Mel, Michael Short

Most studies on optimal design of grid-connected distributed energy systems (DES) have relied on simplifications such as the Direct Current (DC) approximation of alternating current (AC) power flow or balanced AC power flow formulations to avoid nonlinear constraints. A few contributions considering more realistic AC power flow models employ iterative linearisations derived from local power flow solutions and prior knowledge of the design. Here we propose a combined framework for optimising the designs of DES connected to low-voltage distribution networks, while simultaneously considering nonlinear multiphase optimal power flow (MOPF), which captures the inherent phase imbalances in distribution networks. A new algorithm is proposed for obtaining reliable local solutions using regularised complementarity reformulations of operational constraints containing binary variables, which enables the use of large-scale nonlinear solvers and eliminates the need for iterative linearisations and prior knowledge of DES design. DES design models based on DC approximations, unbalanced MOPF or balanced optimal power flow (OPF) formulations are tested using a modified unbalanced IEEE EU low-voltage network. The MILP with DC approximations yields an infeasible operational schedule when tested against MOPF. Despite the increased complexity, DES with MOPF obtains the best solution with greater integration of solar capacity and reduced total annualised cost compared with DES with OPF. The new algorithm with complementarity reformulations achieves a 19% improvement versus a bi-level model for DES with OPF, where the binary topology in the nonlinear model is fixed. Thus, combined framework produces DES designs that respect realistic unbalanced power flow constraints in distribution networks.

3 - Evaluation of the European energy security using a robust multicriteria decision aid framework
Eleftherios Siskos, Antoine Desbordes, Peter Burgherr, Russell McKenna

The resilience and security of the energy system are currently at the center of international interest and top priorities, especially for Europe. As such a complicated and multidimensional concept, the fortification and enhancement of energy security are of paramount importance for energy policy making. Under such circumstances, the need for transparent and holistic evaluation frameworks to benchmark national energy security and appraise the achieved improvement arises. This research proposes a multicriteria decision aid methodology to evaluate and rank the energy security performance of the 35 countries of the European Network of Transmission System Operators for Electricity (ENTSO-E), based on several evaluation criteria. Due to the heterogeneous and complex nature of the criteria, the potential redundancies and synergies between them are accounted for, by introducing the notion of criteria interactions. Within this context, a synergy of preference elicitation techniques is developed, in order to support the application of the Choquet integral utility function, which is approached as an importance indicator. The elicitation techniques combine a procedure, based on the rationale of the Simos method and a novel interactions identification and quantification framework, including direct pinpointing of the criteria interactions and the addition of certain heuristic questions. Simultaneously, the stability of the evaluation model and the achieved results is assessed using a robustness control methodology. The framework adds to the whole assessment the subjective nature of the preferences of a European energy expert, serving the objective to achieve a personalized energy security ranking and provide guidelines and areas for improvement at a country level.

4 - Residential electricity distribution and trading with prosumers assisted by blockchain technology
Phil Zheng

Distributed power generation via renewable resources enhanced by energy storage has gradually become the most promising way for decarbonization in residential electricity consumption. There is a fast growing interest and pressing between utilities and electricity prosumers, who are both electricity producers and consumers. This talk discusses a design allowing energy producers within the local power networks to safely transact with neighborhood households. In other words, the users who have a redundant amount of power can sell it to other users who need power at a fairer price. At the same time, all prosumers are able to purchase power from utilities when experiencing shortage of generation due to uncertainties, e.g., weather. We show that such local trades provide benefits to both electricity buyers and sellers. In addition, we show that this scheme can be managed without a central electricity exchange. A blockchain based peer-to-peer platform is designed. As supporting evidence we provide experimental data—the simulation of the market and its infrastructure using blockchain Hyperledger's Fabric framework.

■ TB-09

Thursday, 10:00-11:30 - 10.50 Raum 604

MODEX - comparison of energy models

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Hans Christian Gils*

1 - Case study on the model parametrization for modeling cross-border redispatch - insights from a grid model comparison experiment
Franziska Flachsbarth, Christina Wolff, Hannes Hobbie, Jonas Mehlem, Lukas Weber, Dominik Möst, Albert Moser

The integration of increasing shares of renewable energies into the energy system while maintaining a high level of security of supply poses a challenge for the grid operators. It requires an effective operation of the electricity grids. The methods for modeling the operation of (extra-) high-voltage grids are constantly being further developed. The results are therefore dependent on differences in modeling methods. This research aims to show the impact of model parametrization on a case study to model cross-border redispatch. We apply a linear transmission grid model for the German electricity transportation system comprising more than 500 grid nodes to study this impact. The optimization of remedial actions is carried out in an hourly resolution of 8760 hours a year, applying a rolling horizon modeling approach. Penalty costs are involved to derive a merit order of remedial actions according to the regulatory framework. The parametrization of these costs have a significant impact on the use of remedial actions, especially in border regions. The effects of model parameterization and formulation on congestion management are shown exemplarily for one model. The steps of the analysis included: (1) model comparison, (2) investigations of model results, (3) set up of model experiments, and (4) results interpretation by deriving key findings and recommended actions for modelers. Results indicate that data parametrization for cross-border redispatch can significantly impact model results concerning congestion management volumes and the geographic distribution of the respective measures. The analysis also highlights the need to calibrate key model parameters thoroughly.

2 - Comparison of different methods of spatial disaggregation of electricity generation and consumption time series
Oriol Raventos

We present a methodology to compare regionalization techniques of input data for photovoltaics, wind and electrical load for energy system models. We also compare data assignment techniques to the power grid nodes. We further introduce two invariants to evaluate the outcome of the regionalization process at the NUTS 3 level (one invariant for the annual profiles and one for the installed capacities). This methodology is applied to compare regionalization and assignment workflows of eight different German energy system models using simple parameters, without explicit knowledge of grid topology. Our results show that the resolution of the input data and the use of a top-down or a bottom-up approach are the most determinant factors in the regionalization process.

This work done as part of the project MODEX-Net.

3 - Comparing the optimal capacity expansion of six power sector models: lessons learned

Jonas van Ouwerkerk, Hans Christian Gils, Hedda Gardian, Martin Kittel, Wolf-Peter Schill, Alexander Zerrahn, Alexander Murmann, Jann Launer, Laura Torralba-Díaz, Christian Bussar

The decarbonization of the European power sector requires increased shares of renewable generation in combination with additional system flexibility. Many power sector modeling tools exist that are capable to optimize capacity expansion. However, models are always an abstraction from the real world system which leads to divergent modeling approaches and detail in technology modeling. This poses the question, of whether different model representations are capable of reliably delivering robust solutions. Therefore, in our study, we compare six mature power sector models in a stylized comparison exercise by feeding them with harmonized input data sets. With four stylized test cases, we analyze the expansion of basic power sector technologies. This includes the expansion of thermal power plants, short- and long-duration electric energy storage, thermal power plants in competition with short-duration storage, and transmission. To strengthen the robustness of our analysis three different weather years are considered. The results show that deviations between models are mainly driven by different detail of technology modeling. Fixed energy-to-power ratios lead to substantially fewer investments into energy storage. For transmission, the simplified net transfer capacity model tends to underestimate the true need for grid expansion. Furthermore, models with a pre-defined dispatch order are less flexible than linear programming-based models which leads to increased expansion costs. Overall the results are robust as the pattern between models is very similar across all weather years. Despite the stylized test cases within this model comparison, we expect that the observed effects are also valid for more complex scenarios, although they might be less visible.

4 - The effect of different modeling approaches and model scopes on the results of large-scale power system optimization models with sector coupling

Hans Christian Gils, Hedda Gardian

Model-based scenario analyses of future energy systems often come to deviating results and conclusions when different models are used. This may be caused by heterogeneous input data and by inherent differences in model formulations. The representation of technologies for the conversion, storage, use, and transport of energy is usually stylized in comprehensive system models in order to limit the size of the mathematical problem, and may substantially differ between models. This contribution presents a systematic comparison of nine power sector optimization models with sector coupling. In two experiments, we analyze the impact of differences in the model scope, representation of technologies, and optimization approaches on model outcomes. The experiments use fully harmonized input data and highly simplified system configurations to isolate and quantify model-specific effects. In the first experiment, individual flexibility options are investigated based on a comprehensive qualitative analysis of the models and their differences. Considering highly reduced test cases, it was possible to isolate and quantify model-specific effects. Building on the technology-specific analyses, more complex scenarios are considered in the second experiment. Despite the high number of models and interacting model differences, result deviations can still be related to model characteristics. We find that differences in modeling approach and the representation of specific technologies lead to comparatively small deviations, whereas a heterogeneous model scope can have a much more substantial impact. In summary, our results can provide a better understanding of the effect of different modeling approaches and thus contribute to the interpretation of model results.

■ TB-10

Thursday, 10:00-11:30 - 20.30 SR 0.014

Pick up and delivery problems & Facility location problems

Stream: Logistics
Invited session
Chair: *Viktor Bindewald*

1 - Considering Customer Choice in Mobile Facility Location

Viktor Bindewald, Stefan Nickel, David Sayah

In this talk we present a new multi-period facility location problem: Mobile service facilities with customer choice (MSFCC) which consists in closing, reopening, and relocating mobile service facilities within a given discrete planning horizon. Furthermore, MSFCC allows multiple capacity levels at a candidate location, thereby enabling location planners to react to varying demand over time by dynamically increasing or decreasing staff, equipment etc. Customer choice behavior is modeled using the well-known multi-nomial logit (MNL) choice model. In particular, the parameters of the MNL model may depend on when and where a customer chooses to patronize a facility (or to opt out). MSFCC is fairly versatile supporting location planners in a variety of application contexts, e.g., positioning mobile public libraries, healthcare facilities, pop-up stores or food trucks. Since the problem is a difficult MINLP, it is computationally challenging when solving even medium-sized instances with out-of-the-box NLP solvers. Therefore, we also present an exact solution approach to MSFCC problem which is based on a generalized Benders decomposition. We will show preliminary computational results indicating the competitiveness of our decomposition algorithm.

2 - Enhancing the General Pickup and Delivery Problem with a Rule-based Trip Definition

Alexander Kleff

There are very diverse practical applications of the vehicle routing problem (VRP), and this has led to a plethora of problem variants that has been discussed in the literature. From a commercial point of view, a crucial point is the question which of these problem variants should be covered by a commercial VRP solver if that solver is to be designed to help not just one but many clients with their different optimization needs.

In our talk, we will present the PTV-PDP, that is, the 'partitioned tour variant' of the pickup and delivery problem (PDP). It is the basic problem that the commercial optimization tools of the PTV Group solve, a vendor of software solutions for logistics and mobility. Depending on the client's use case, it allows for creating structurally very different tours, that is, different answers to the question 'How does a valid tour look like?'.

One aspect of this problem is that there is no central depot but every vehicle has its individual start and end location (as in the General PDP, GPDP). An even more important characteristic is that it introduces the notion of trips in the GPDP and thus generalizes both the GPDP and the multi-trip VRP. In the PTV-PDP, every tour is partitioned into trips by means of a few rules. One of these rules is that the vehicle must be empty both at the beginning and at the end of the trip. Another rule is that a trip begins/ends either at the vehicle start/end location or at a depot. Here, the trip delimiting property is the main property that distinguishes depots from customer sites.

In our talk, we will describe the exact definition of the PTV-PDP, highlight the characteristics and benefits, outline the problem variants that the PTV-PDP generalizes, and show how restrictions on trip-level can be considered.

3 - An Integrated Facility Location and Service Network Design Problem

Alexander Helber, Marco Lübbecke

In freight networks costs are mainly driven by pickup and delivery operations between customers and facilities as well as line haul operations between facilities. Both types of operations depend on the locations of the facilities. We consider an integrated problem where facility locations have to be selected that not only minimize the cost of (simplified) pickup and delivery operations but also the design of the service network between the facilities. This includes the decision of which facilities should operate as hubs. Natural extensions are the

consideration of uncertainty in demands or availability of links in the network. The topic is currently developed jointly with a logistics company, adding uncertainty in scope. We present our first steps regarding this topic.

■ TB-11

Thursday, 10:00-11:30 - 10.50 Raum 602

Integrated Sustainability Assessment of Future Energy Supply Strategies

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Evangelos Panos*
Chair: *Stefan Hirschberg*

1 - Sustainability Assessment of Technologies and Scenarios for Passenger Transport: The Swiss Case

Stefan Hirschberg, Romain Sacchi, Kannan Ramachandran, Matteo Spada, Evangelos Panos, Christian Bauer, Peter Burgherr, Tom Kober

Sustainability of the energy sector is a central objective of policies of many countries. In Switzerland the commitment to sustainability goals is explicitly stipulated in the federal Constitution. The primary focus of the current energy policy is reaching net zero Greenhouse Gas emissions in 2050. The transport sector must massively contribute to reaching this goal. Besides climate protection, a broader set of environmental, economic and social criteria needs to be covered. We use detailed technology assessment based on such methods as Life Cycle Assessment (LCA), Impact Pathway Approach (IPA) and Risk Assessment (RA). This is supported by our major databases, including the life cycle inventory database ecoinvent as well as ENSAD covering accident risks. Technology advancements and scenario-dependent performance are consistently treated. For the generation of scenarios we use the technology-rich bottom-up Swiss Times Energy Model (STEM) and the global model REMIND. The derived environmental, economic and social indicators for technologies and scenario-dependent mobility fleets are used as inputs to Multi-criteria Decision Analysis (MCDA). Furthermore, external as well as total costs are derived. Insights include among others rankings of technology options and scenarios, and sensitivity mapping based on different preference profiles. This leads to trade-off outcomes representing a compromise between radical climate protection goals and broader sustainability objectives.

2 - Projections of environmental impacts of biofuels across scenarios using prospective LCA

Vassilis Daioglou

Integrated assessment models (IAMs) have been used to project plausible futures, with a focus on how socioeconomic, technological, and policy developments help mitigate climate change. In these projections IAMs typically show that biofuels can play a very important role in future energy systems. However, biofuels may have significant environmental impacts stemming from their requirement for land, agricultural production, and complex chemical processes, leading to an increasing need for analyses of their broader environmental effects. In this work we combine the IMAGE IAM with LCA to enable consistent assessment of environmental impacts of future biofuel supply. The aim is to use the IAM to inform LCA in terms of appropriate assumptions concerning future land use, energy supply, and transport systems.

The analysis has been conducted for a number of scenarios (baseline, 2'C, 1.5'C), and four different biofuel technologies expected to play an important role in future energy systems (first generation and advanced biofuels). The results indicate that changing land-use, transport and power supply systems influence the environmental impacts of biofuels across a number of dimensions. Increasing crop yields lowers impacts arising from land use, and cleaner energy systems reduce the impacts from conversion and distribution. However, cleaner future energy systems also imply that some positive impacts of the by-products of 1st generation biofuels are also further limited, since they tend to replace products which are produced under improved circumstances in the future. The results also show significant regional variation, further highlighting the importance of the energy and land-use context when assessing the sustainability of biofuels.

3 - Future energy supply scenarios and their impacts on in the life-cycle performance of transport

Romain Sacchi

Strategies for future energy supply will impact the environmental performance of virtually all products and services, among which those related to mobility. To correctly evaluate the performance of future mobility services, integrating these strategies and their implications with respect to climate change, land and resource use is therefore crucial.

Using the IAM-LCA integration framework premise, the life-cycle analysis of future individual and collective means of transport is enriched with information from prospective scenarios. This includes information that directly impacts transport activities, such as regional electricity and liquid and gaseous fuel mixes, but also information on the spatial distribution and use of land and its impacts on the production of liquid biofuels and biomass-based power, the emergence of novel synthetic fuels as well as the need for additional extraction of metals involved in the development of systems that produce and consume electricity.

This framework is notably useful for highlighting potential trade-offs between the climate change mitigation objective pursued by the IAM scenario, and any increase of impacts with respect to other environmental recipients.

The presentation will walk the audience through the information workflow, from reading in prospective scenario information to its inclusion in LCA models. It will showcase and explain the influence of energy supply strategies on different environmental indicators, besides that of Climate change.

4 - Spatial trade-offs in national wind power deployment in times of biodiversity and climate crisis

Kristina Haaskjold, Kristine Grimsrud, Cathrine Hagem, Henrik Lindhjem, Megan Nowell

The economic profitability of wind power differs spatially depending on the wind conditions and necessary investments in turbines, infrastructure, and grid. At the same time, the deployment of land-based wind power raises several environmental concerns depending on the siting of the WPPs, such as noise, impaired landscape aesthetics, loss of unfragmented land, and impacts on wildlife and biodiversity. In addition, the construction of WPPs in natural areas affects carbon storage, both by reducing carbon stored in trees and emissions from drained marshland.

This analysis determines the cost-effective deployment of WPPs across Norway from a technological-social economic perspective while also taking into account the climate and biodiversity concerns associated with the WPP deployment. The analysis permits the inclusion of local nuisance costs and the cost of carbon emissions associated with each WPP as cost parameters in the TIMES-Norway energy system model and the possibility of adding constraints to prevent loss of unfragmented land and loss of land that is important for wilderness and biodiversity. This social cost is determined as a counterfactual analysis for WPPs that already are built and for future potential WPPs where the licensing process is completed or underway.

The present paper contributes to the literature by suggesting systems for how to evaluate and include various kinds of environmental impacts, more comprehensively assessed than previously, into the regulator's decisions on domestic siting of wind power production. By employing an energy system model, we can explicitly find the social cost of deviating from a siting, which would be privately most profitable and that is minimizing the system cost of providing a certain amount of wind power.

■ TB-12

Thursday, 10:00-11:30 - 10.50 Raum 701.3

Optimization in public transport

Stream: Mobility and Traffic
Invited session
Chair: *Daniela Gaul*

1 - Solving Train Dispatching by Column Generation

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. In the process, train paths are varied in their spatio-temporal course. The dispatching problem now consists of selecting conflict-free train paths with minimum delay. We introduce a binary linear decision model. 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. Instead of modelling pairwise conflicts, we get a stronger MIP formulation if we use conflict cliques. The combinatorics of speed profiles and variation of departure times results in a large number of possible train paths, so that the column generation method is used here. New train paths within the pricing-problem can be calculated by using shortest path techniques. Thus, 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 heuristic approach via dynamic programming as well as a MIP solution method. Numerical results are presented.

2 - Quality and Cost criteria-driven optimization of the integrated timetabling and vehicle scheduling problem by an extendable evolutionary scheme with mutation patterns
Lucas Mertens, Bastian Amberg, Natalia Kliewer

This study focuses on the bridge between tactical and operational public transport planning by solving the Timetabling Problem (TT) and Vehicle Scheduling Problem (VSP). Given a network and line design, the TT aims at achieving a high range of passenger service while keeping the total anticipated costs for serving the timetable reasonable. The VSP allocates service trips to specific vehicles at minimal costs. An integrated optimization can lead to significant cost savings compared to sequentially solving the TT first and the VSP subsequently. We propose an adaptive modular evolutionary scheme for integrated optimization of the already NP-Hard subproblems. Various heterogeneous mutation operators are utilized within the scheme, and their impact on the computed timetable and corresponding vehicle schedule is evaluated during the solution process. The quantity and order of applying each mutation operator is determined by its past performance. In addition to evaluating the specific performance of each mutation operator, patterns of promising heterogeneous sequential mutations are elaborated and collectively applied to an individuum within the same generation. In the study, we aim to plan good headways and reasonable transfer times for the TT in addition to the relevant cost criteria. This extension did not increase the computational time significantly but further improved the solution quality. Overall, solving the integrated TT and VSP for real-world instances by utilizing the adaptive modular evolutionary scheme led to a significant cost reduction while keeping the quality of the timetable equally good. Further quality criteria can be considered easily within this approach to suit any given requirements within reasonable computation times.

3 - Ridepooling and public bus services: A comparative case-study
Daniela Gaul, Hanno Gottschalk, Kathrin Klamroth, Michael Stiglmayr

This case-study aims at a comparison of the service quality of timetabled busses as compared to on-demand ridepooling cabs in the late evening hours in the city of Wuppertal, Germany. To evaluate the efficiency of ridepooling as compared to bus services, and to simulate bus rides during the evening hours, transport requests are generated using a predictive simulation. To solve the resulting dynamic dial-a-ride problem, a rolling-horizon algorithm based on the iterative solution of Mixed-Integer Linear Programs is used. A feasible-path heuristic is used to enhance the performance of the algorithm in presence of high request densities. The computational study allows an estimation of the number of cabs needed to realize the same or a better service quality as the bus system, depending on the weekday and the time of day.

4 - Automatic generation of a service intention in public transport with integrated travel chains
Stephan Buetikofer, Raimond Wüst, Stefano Gioia

Automation and digitization in the development of the transport service offer for public transport is a challenge in the future. The goal is to achieve optimal and consistent planning across all process steps and time horizons to increase the degree of automation and the service quality. 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. In each step, decisions are made about possible passenger travel chains (e.g. connections). We focus on the first two steps. These steps produce the transport service offer. We call this offer according to the literature service intention. The service intention is a functional description of the timetable in the form of train runs and relations between them. It was shown that the service intention is a suitable input for the timetabling process. For both steps there are mathematical optimization models support the planning decisions individually. However, there is still little literature on the interfaces of these models. In this work we want to demonstrate that it is possible to use these models systematically to generate the service intention in an automated way respecting the travel chains (e.g. in the form of suited connections) defined in the system split resp. the line planning step. Further on, we will discuss the motivation for this work and illustrate the methodology with an suited example.

■ TB-13

Thursday, 10:00-11:30 - 20.30 SR -1.025

OR in practice

Stream: Software Applications and Modeling Systems
Invited session

Chair: *Jens Schulz*
Chair: *Michael Bussieck*

1 - Research & Development Activities at GAMS
Frederik Fiand, Michael Bussieck

GAMS has been providing its users with cutting edge optimization technology for several decades. To this end, it is necessary to keep a constant eye on new promising technologies and developments. In recent years, GAMS has therefore increasingly participated in multidisciplinary research projects that bring together specialists from areas such as mathematical optimization, high-performance computing, machine learning, visualization and quantum computing. The application areas are also diverse and address relevant challenges of our time, such as logistic planning problems or energy system analysis, a very active research area in which numerous scientists are developing sustainable solutions for tomorrow's energy systems.

This presentation gives an overview of various recent research projects with GAMS participation. We give insights how projects funded by the Federal Ministry for Economic Affairs and Climate Action such as BEAM-ME, UNSEEN, and ProvideQ, the research campus MODAL funded by the Federal Ministry for Education and Research, or our cooperation with the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA) led to concrete developments giving our project partners access to pioneering technologies through GAMS.

2 - Rapid Optimization Projects
Jens Peter Kempkes, Ingmar Steinzen, Stefan Bunte

The process, management and tools experience of some hundredbb optimization projects distilled to hints and best practices. Let's discuss how to do successful optimization software projects more efficiently. This presentation will also include a demo of the OPTANO Platform, a low-code environment to rapidly create enterprise ready optimization software.

3 - The emerging impact of quantum computing on operations research and some resulting opportunities
Dirk Zechiel

Quantum computing holds many promises for Operations Research, opening up opportunities to extend today's models to better reflect the "real" world and solve problems previously unsolvable or not solvable in commercially useful times.

However, it also presents a number of challenges including 1) existing code doesn't run on quantum computers, 2) it isn't clear which types of problems will benefit most from quantum computing (and even which

type(s) of quantum computers will dominate), and 3) when quantum computers will mature enough to be useful for specific classes of problems.

This talk will discuss the state of quantum computing, opportunities to take advantage of advances in quantum technology on today's classical computers, managing the development and solving of models in an uncertain and rapidly changing hardware environment, and preparing for the much-discussed "quantum supremacy".

4 - Mixed variables methods applied to industrial split delivery routing within LocalSolver
Guillaume Crognier, Olivier Rigal

LocalSolver is a global optimization solver which combines both exact and heuristic methods to solve all kinds of optimization problems. Its model-and-run approach allows users to solve combinatorial, continuous or mixed variables problems even for large instances. A recent solver evolution was to implement a dedicated method for mixed variables problems which continuous part is linear. The goal of this paper is to show how efficient these this method can be when applied on large scale industrial instances of SDVRP (Split Delivery Vehicle Routing Problem).

The main idea of the method exploits the already existing local search algorithm within the solver. It runs in two steps. First, a local search movement is applied to the combinatorial variables only (ie all variables that are not continuous). Then, once all the combinatorial variables have been fixed, the corresponding subproblem is assumed linear regarding the continuous variables. This subproblem is solved with a dual simplex algorithm. This method is then sped up with simplex warm start between two iterations and Farkas rays analysis.

The Split Delivery Vehicle Routing Problem (SDVRP) falls in the scope of the above algorithm. Structural constraints and customers order can be represented with combinatorial variables and the delivered quantities with continuous variables.

This approach proved to be extremely efficient for a SDVRP-like problem coming from one of LocalSolver Japanese customers. This method was benchmarked against pure local search in LocalSolver 10.5 and a compact MIP model solved with Gurobi 9.1. Instances have up to 100 customers and 120 trucks. The presented method was the only one capable of providing non trivial solutions to the biggest instances in less than 15 minutes.

■ TB-14

Thursday, 10:00-11:30 - 10.50 Raum 702

Robust and Bilevel Optimization I

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Marc Goerigk*

1 - Multi-Stage Adjustable Robust Optimization: New Tractable Policies and Approximation Bounds
Simon Thomä, Grit Walther, Maximilian Schiffer

In practice, most decision-making problems have to be solved in view of uncertain parameters. Over recent years, robust optimization emerged as a prominent and scalable framework to inform such decisions. Against this background, we study piecewise affine policies for multi-stage adjustable robust optimization (ARO) problems with non-negative right-hand side uncertainty. First, we construct new dominating uncertainty sets and show how the ARO problem can be solved efficiently with a linear program, when uncertainty is replaced by these new sets. We then demonstrate how solutions for this alternative problem can be transformed to solutions for the original problem. By carefully choosing the dominating sets, we proof strong approximation bounds for our policies that extend many previously best known bounds for the two-staged problem version to its multi-stage setting. Moreover, the new bounds are - to the best of our knowledge - the first bounds shown for the general multi-stage ARO problem considered. In two numerical experiments we find that our piecewise affine policies can be computed by a factor of 10 to 1,000 faster than affine policies, while often yielding comparable or even better results. We observe particularly high improvements on instances that exhibit certain synergistic effects and allow for universal recourse decisions. Especially for hypersphere uncertainty sets our new policies perform well and sometimes even outperform affine adjustable policies by up to a factor of two.

2 - Recycling Valid Inequalities for Robust Binary Optimization with Budget Uncertainty
Timo Gersing, Arie Koster, Christina Büsing

Since its introduction in the early 2000s, robust optimization with budget uncertainty has received a lot of attention. This is due to the intuitive construction of the uncertainty sets and the existence of a compact robust reformulation for (mixed-integer) linear programs. However, despite its compactness, the reformulation performs poorly when solving robust integer problems due to its weak linear relaxation.

To overcome the problems arising from the weak formulation, we propose a new procedure to derive new classes of valid inequalities for robust binary optimization problems. For this, we recycle valid inequalities of the underlying non-robust problem such that the additional variables from the robust formulation are incorporated. The valid inequalities to be recycled may either be readily available model-constraints or actual cutting planes, where we can benefit from decades of research on valid inequalities for classical optimization problems.

We first demonstrate the strength of the inequalities theoretically, by proving that recycling yields a facet-defining inequality in surprisingly many cases, even if the original valid inequality was not facet-defining. Afterwards, we show in a computational study that using recycled inequalities often leads to a significant improvement of the computation time when solving robust optimization problems.

3 - On the Complexity of Robust Multi-Stage Problems in the Polynomial Hierarchy
Lasse Wulf, Marc Goerigk, Stefan Lendl

As single-stage robust optimization has been well studied, researchers in the area of robust optimization have turned their attention towards multi-stage problems. These are robust problem where the decision process of the decision maker is split into two or even more stages. Examples for problems of this kind are adjustable two-stage optimization and recoverable optimization.

These mentioned multi-stage problems are solved by optimizing an expression with alternating min/max quantifiers and therefore naturally fall into some stage of the polynomial hierarchy. Despite this, almost no hardness result with respect to the polynomial hierarchy is known for robust multi-stage problems. If a problem is hard with respect to at least the second stage of the polynomial hierarchy, then (under common complexity assumptions) there cannot exist a polynomial size integer program for the problem and it is less likely to be efficiently tackled by IP-solvers.

In this work, we make a first step towards understanding the complete picture by showing that several robust two-stage problems are hard for the third stage, while several others are not. We also show that allowing uncertainty in the constraints (in contrast to the case where uncertainty is only allowed in the objective) can turn a NP-hard problem into a more difficult problem. Our results also extend to more than two stages.

4 - A Penalty Branch-and-Bound Method for Mixed-Integer Quadratic Bilevel Problems
Andreas Horländer, Martin Schmidt

Bilevel problems model situations in which two decision makers exist, whose optimization problems are nested within each other. Due to this special structure, bilevel problems have many applications in economics and technology. In this talk, we propose an algorithm for solving bilevel problems with mixed-integer quadratic upper level as well as quadratic and continuous lower level. The method is based on a classic branch-and-bound procedure, where branching is performed on the integer constraints and on the complementarity constraints resulting from the KKT reformulation of the lower-level problem. However, instead of branching on those constraints as usual, suitably chosen penalty terms are added to the objective function. We prove the correctness of this method and present its applicability by some first numerical results.

■ TB-15

Thursday, 10:00-11:30 - 10.50 HS 101

Discrete Optimization

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Sven Krumke*

1 - Time Disjoint Paths
Christoph Geis, Sven Krumke

The edge disjoint paths problem (EDPP) is an important problem in graph theory with many applications. Given a graph, the EDPP asks for the maximum number of edge disjoint paths from a given source vertex to a given vertex node. We consider a dynamic version of the EDPP, called the time disjoint paths problem (TDPP), where for each edge we are given a traversal time required to pass through this edge, and we are looking for a set of paths such that two paths may use the same edge, but may not use the same edge at the same time. We call such paths time disjoint. One application of the TDPP is in a system of (narrow) roads or railways where one searches for routes for vehicles, such that no two vehicles are allowed on the same road at the same time.

We provide a complete complexity classification of the TDPP. Specifically, we show that the decision version of the TDPP is NP-complete even under strong assumptions on the structure of the graph and/or the given traversal times on the edges. However, if we fix the number of sought-after paths, require time to be discrete and only consider paths that are completed before a given time horizon, we can construct an algorithm solving the TDPP in time polynomial in the size of G and pseudopolynomial in the time horizon. Our algorithm uses the principle of dynamic programming and will compute sets of time disjoint paths for any tuple of final edges for the paths and any time horizon up to the given time horizon. We show how to adapt the algorithm to similar problems that ask for paths in a dynamic graph where instead of time-disjointness one requires a certain collision-avoidance which is given by an oracle. This yields an oracle-polynomial time algorithm for a large class of dynamic path-problems.

2 - On the Complexity of Finding Short Branch-and-Bound Proofs
Maximilian Gläser

We explore the complexity of finding small branch-and-bound-trees using variable disjunctions. We show that approximating the size of a smallest branch-and-bound tree cannot be approximated within a certain exponential bound, unless the exponential time hypothesis fails. Next, we review the notion of automizability from proof theory, which formalizes the ability to efficiently guide a branch-and-bound algorithm during its execution, even if short proofs do not exist. We note that many results transfer from the proof system of treelike resolution, hence branch-and-bound is quasi-automatizable, but not automatizable. Moreover, we show that computing the size of a shortest branch-and-bound tree is #P-hard, even when restricted to matching polytopes.

Lastly, we present a technique to give lower-bounds for both branch-and-bound with variable disjunctions and with general disjunctions, recovering several results from the literature. In the case of variable disjunctions, we give an example of a class of polytopes for which the bounds attained by our method are tight.

3 - On the complexity of the robust shortest path and robust perfect b-matching problem under consistent arc constraints
Sabrina Schmitz, Christina Büsing

In this talk, we consider the robust shortest path (RSP) and robust perfect b-matching (RPM) problem under consistent arc constraints. In both problems, we consider a set of so-called fixed arcs as well as a finite set of scenarios which represents the uncertainty. In the RSP problem, a shortest path is sought for each scenario where the start and end vertices are subject to uncertainty. In the RPM problem, a b-matching is sought for each scenario where the b-values are subject to uncertainty. To satisfy the consistent arc constraints we require either the use or the non-use of a fixed arc in the shortest paths or b-matchings of all scenarios. We prove that the RSP problem is in general NP-complete, even if we consider two scenarios and only one fixed arc. For the special case of an acyclic digraph, we provide a polynomial time algorithm. For the RPM problem, we show the NP-completeness for bipartite graphs with unit edge capacities, even if only two scenarios are considered. If zero-one degree restrictions are given, we further show the NP-completeness for bipartite graphs if a constant number of scenarios is considered and for general graphs if only two scenarios are considered.

4 - The traveling salesman problem with memory
Anja Fischer

In this talk we introduce a new variant of the traveling salesman problem (TSP). Given points in the Euclidean plane, some minimal radius and a memory level we look for a shortest tour such that each point is visited exactly once and such that the memory and distance requirements are satisfied. Indeed, the distances between neighboring points along the tour must be larger than a given value and after visiting some point it is not allowed to enter the area of the circle around that point in a given number of steps. This problem is motivated by an application in laser beam melting and can be seen as an extension of the TSP with forbidden neighborhoods. We present different formulations of this problem and show how to use geometrical properties in order to derive valid cutting planes improving the basic models. Apart from this we consider some special cases related to the application. At the end we show some preliminary computational results.

■ TB-16

Thursday, 10:00-11:30 - 20.30 SR -1.012

Continuous and Global Optimization

Stream: Continuous and Global Optimization
Invited session
Chair: *Mario Jelitte*

1 - Constrained and unconstrained blackbox optimization
Emeline Tenaud

Black box functions are functions for which the analytical formula is not available: only an oracle is able to evaluate them. These functions are usually computationally expensive and the number of evaluations of the oracle is often limited, so each point to be evaluated must be chosen carefully. In LocalSolver, a global optimization solver using exact and heuristic methods, the approach implemented is based on surrogate modeling. In this method, the objective function is approximated by a radial basis function (RBF). The algorithm alternates between exploitation phases, where the surrogate model is optimized, and exploration phases, allowing to explore the search space and avoid local optima. The resulting submodels are then solved with the LocalSolver nonlinear solver to generate a new point to evaluate. Constraint handling has been added for blackbox models in recent versions of LocalSolver. There are two types of constraints: - Analytical constraints, for which the analytical formula is available. They can be written directly in the solver formalism. As the solver gains more knowledge about spatial search, it can avoid evaluating points that do not satisfy the analytical constraints, thus saving the limited evaluation budget at our disposal. - Concerning black box constraints, they are also approximated by an RBF surrogate. A margin criterion is defined at each constraint to help satisfy the feasibility of the model. This criterion is adjusted at each iteration according to the feasibility of the previously evaluated point, which increases the chances of obtaining the optimum even if it is located at the limits of the solution space. The implemented approach generates good results comparable to those obtained by state-of-the-art black box optimization solvers.

2 - Implementing an optimization solver for hierarchical multi-objective problems : the strange case of the optimality tolerance.
Nikolas Stott

Hierarchical multi-objective optimization deals with problems that have several objective functions that are ordered by decreasing priority. Solving these problems exactly requires several steps : one optimization problem is solved per objective, where that objective is optimized and every previous objective is constrained to be equal to its optimal value ("optimality constraints").

All numerical optimization solvers rely on numerical tolerances. The optimality tolerance limits the computation time: the solver stops when the gap between the solution and the lower bound is small enough.

This work explores the mixing the two concepts, i.e. when each step of the multi-objective problem resolution is solved up to an optimality tolerance. We describe the impact of this tolerance on the solving process, on the optimal solutions and on practical implementation requirements. We illustrate these phenomena with examples and experiments with various solvers.

First, the optimality constraints must be relaxed by only enforcing a one-sided bound, either by its primal value, or by shifting its dual value. We show that neither approach is satisfactory: the solutions tend to take suboptimal values, especially when objectives are contradictory.

Commercial solvers often run several algorithms in parallel. This can add uncertainty and lead to different optimal solutions depending on the run. This effect is amplified in a multi-objective setting, and it may lead to disjoint primal-dual intervals for a same objective. Moreover, exact optimal solutions may be proven sub-optimal and the gap between the true optimal value and its approximate counterpart may be arbitrarily large.

3 - Weakest constraint qualifications in multi-objective optimization
Maximilian Volk, *Oliver Stein*

In single-objective optimization, the Guignard Constraint Qualification (GCQ) is the weakest constraint qualification guaranteeing that a local minimal point is a KKT point, i.e., that the multiplier associated with the objective function is strictly positive. In multi-objective optimization however, the GCQ is not sufficient to guarantee positive objective function multipliers at local weak, proper, and even strict Pareto optima. This fundamental difference is known as the gap between single- and multi-objective optimization. Recently, Haeser and Ramos introduced a multi-objective generalization of the regular normal cone and derived the weakest constraint qualifications which guarantee positive and strictly positive objective function multipliers at local weak Pareto optimal points. In a similar fashion, in this talk, a family of multi-objective regular normal cones is introduced and investigated. Using these generalized normal cones, the weakest constraint qualifications yielding strictly positive multipliers at local proper and strict Pareto optima are derived.

4 - Constrained Lipschitzian Error Bounds and Noncritical Solutions of Constrained Equations
Mario Jelitte, *Andreas Fischer*, *Alexey Izmailov*

For many years, local Lipschitzian error bounds for systems of equations have been successfully used for the design and analysis of Newton-type methods. There are characterizations of those error bounds by means of first-order derivatives like a recent result by Izmailov, Kurennoy, and Solodov on critical solutions of nonlinear equations. We aim at extending this result in two directions which shall enable, to some extent, to include additional constraints and to consider mappings with reduced smoothness requirements. This leads to new necessary as well as sufficient conditions for the existence of error bounds. Finally, we will formulate conditions, ensuring that a min-reformulation with slack-variables of a nonlinear complementarity problem provides a constrained Lipschitzian error bound.

■ TB-17

Thursday, 10:00-11:30 - 20.30 SR -1.011

OR and energy systems in low-income and lower-middle income countries

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

1 - Renewable energy for e-fuels from Africa: Potentials for coverage of internal African energy demand and export of energy carriers
Veis Karbassi, *Philipp Trotter*, *Grit Walther*

Large-scale production of e-fuels to enable global decarbonization requires vast amounts of additional renewable resources. Europe, driven by its large demand for e-fuels and limited domestic renewable energy potential has started to implement import strategies for e-fuels from regions with high potential. Africa possesses more than 45% of the global renewable resources while having the world's lowest per capita energy consumption. These resources could be harnessed to satisfy large shares of the continent's domestic energy demand and serve as a large-scale export opportunity. So far, the main focus of energy trading studies considering Africa lies in North Africa (or, more broadly, the MENA region), leaving out the 48 sub-Saharan African countries. Furthermore, most of the available literature on African energy system planning ignores individual, country-specific socio-political factors. Finally, and perhaps most crucially, the extant planning literature has largely failed to study the broader socio-economic development implications of global defossilization for individual African countries. Addressing these three gaps, we present a Linear Programming Multi-Objective energy planning model, which fulfills the African demand through renewable energy carriers and provides excess energy for the production of renewable energy carriers to help reduce the costs of Europe's energy transition. The model minimizes costs and maximizes the equality of economic development impact distribution among African countries. The Pareto-Front resulting from the model demonstrates the trade-offs between the cost-optimal solution and equity. The findings shed light on the ramifications of energy trading scenarios regarding energy carriers and technologies for generation & transportation

2 - A Collaboration Strategy for Hydro, Wind, and Solar Power Plants in the Day-ahead Electricity Market: Real-Life Case of Turkey
Benhür Satir, *Mehmet Özcan*, *Ozan Keysan*

The stochastic nature of renewable electricity energy generation is one of the main challenges related to its trade. Deviation from the forecasted (and committed) generation leads to imbalance cost (IC) in day-ahead markets (DAM). Power plants can cope with IC and maximize their income via collaboration. We developed a linear programming model to analyze the impact of collaboration strategy (CS) on total annual income. We use a real-life data set of Turkey composed of hourly realized and day-ahead planned generations, installed capacities of hydro, wind, and solar power plants, hourly market clearing and system marginal prices in DAM, tolerance coefficient, and coefficient of imbalance set by the regulatory authority. First, we model independent strategy (IS) of power plants using their realized generation values. Then, we model CS by identifying the amount of power generation by hydropower plants as the decision variable-limited by reservoir capacity. Turkey's Energy Market Regulatory Authority (EMRA) used a constant tolerance coefficient (CTC) regime before 2018, where it is fixed and equal to 0.98 for all power plants (implying a 2% tolerance for the imbalances in DAM). After 2018, EMRA adapted the differentiated tolerance coefficient (DTC) regime and set tolerance coefficients as 0.98, 1 (i.e., no tolerance for imbalances), and 0.97 for solar, hydro, and wind power plants, respectively. Our results show that if there is no difference in the forecasts and realized generations, the loss of income due to the imbalance is reduced by 60% and the total annual income is increased by 1.38%. These are upper bounds for IS under perfect forecasting. Under CS, the extra annual income is limited by 0.4% depending on tolerance coefficient regime and power plant type.

3 - A multi-criteria optimisation model to quantify synergies between multiple Sustainable Development Goals through integrated business models
Philipp Trotter, *Tristan Becker*, *Grit Walther*

In 2015, the UN has defined 17 Sustainable Development Goals (SDGs). Current development levels in Africa pose a fundamental threat to reaching a number of SDGs. Driven by slow progress of past development efforts and the vast economic inherent opportunity in development in rural Africa, private sector companies have started to deploy a novel, bottom-up business model for integrated rural development: They integrate infrastructure services such as energy and transport into rural productive value chains and create value for their company as well as across a multitude of SDGs. Here, we formulate a generalised resource-constrained project scheduling model with multiple objectives considering electricity and agricultural product networks to maximise the SDG impact of investments into supply chains and their physical support infrastructure in low-income contexts. Each investment is modelled as a distinct project with a sustainability score. The goal fulfilment toward each SDG is a separate objective function. The model is geographically explicit and features an overall budget constraint. As a case, the model will be applied to perishable food value chains, and will consider joint investments in energy systems, cold chain logistics, investments in conjunction with investments to better understand integration effects. The SDG impacts considered refer to decreasing poverty and hunger (SDGs 1 and 2), improving healthcare, water and energy infrastructure (SDGs 3, 6 and 7), providing decent jobs (SDG8), limiting food loss (SDG12) and climate change mitigation (SDG13) We find significant synergies between these SDGs when integrating development project investment decisions, challenging the dominant approach in practice of siloed, SDG-specific development initiatives.

4 - Robust MARS under Cross-Polytope Uncertainty - An Application in Natural Gas Market
Ayse Ozmen, *Gerhard-Wilhelm Weber*, *Yuriy Zinchenko*

Multivariate Adaptive Regression Spline (MARS) is a form of non-parametric nonlinear regression analysis which does not require particular preconditions on functional relationships among the included response and explanatory variables. There, it is supposed that the input data are known exactly and equal to some nominal values to construct a model. However, both output and input data include noise in real life. Optimization affected by parameter uncertainty is a focus of mathematical programming and a need to handle uncertain data when optimization results are combined within real-life applications. Nowadays, Robustification and Robust Optimization have gained attention from theoretical and practical points of view as a modeling framework in mathematical optimization to immunize against various uncertainties. Underlying the problems to be addressed, data of both the input and output variables are affected by the noise of different kinds such that standard statistical models alone may not be sufficient to ensure trustworthy results due to models' complexity. Consequently, we propose to include parametric uncertainties reflecting future scenarios into MARS that in turn show a great promise for fitting nonlinear multivariate functions, where additive and interactive effects of the predictors are employed to assess the response variable. While in prior studies due to the large complexity of the underlying model we applied what is called a weak robustification, now we suggest exploiting a geometrical and combinatorial approach to allow for a more complete robustification, by formulating Robust MARS (RMARS) under Cross-Polytope Uncertainty. In this study, we use RMARS for energy data and demonstrate its superior performance through a simulation study.

■ TB-18

Thursday, 10:00-11:30 - 20.30 SR -1.013

Solution methods to solve logistic problems

Stream: Logistics
Invited session
Chair: *Pirmin Fontaine*

1 - A Branch-and-Repair Method for 3D Bin Selection and Packing in E-Commerce

Pirmin Fontaine, Stefan Minner

E-commerce is continuously growing and the number of parcels that are shipped around the globe increase every year. Since one major problem in parcel distribution is the high amount of unused space, finding the best-fitting parcel type and the associated packing pattern is important. In the literature, this problem is known as the three-dimensional bin packing problem with rotation. Knowing the right parcel type raises the question of the right parcel type portfolio for a company. We address this question by introducing the three-dimensional bin selection problem (3D-BSP).

To solve the 3D-BSP with rotation of items, we introduce a new decomposition method called branch-and-repair. We show that due to the relaxation a majority of binary decision variables in the master problem can be relaxed and weak combinatorial cuts are avoided without further lifting. Problem-specific acceleration techniques further improve the performance of branch-and-repair.

In the numerical study, we use a dataset by a real-world online retailer and show that branch-and-repair reduces the run time by more than two orders of magnitude compared to the mixed-integer programming formulation. Further, Instances with millions of binary decision variables and constraints are solved efficiently. The sensitivity analysis shows the trade-off between the costs of variety (depending on the number of parcel types) and costs for unused space. Compared to minimizing unused space, minimizing total costs increases unused space by 6 to 27 percent depending on the portfolio size.

2 - Benders algorithm for bi-objective two-stage stochastic optimization problems with multiple scenarios

Ali Sohrabi, Andrea Raith, Richard Lusby

We present a Benders algorithm for bi-objective optimization problems. In this algorithm, a sequence of weighted-sum problems is solved with Benders decomposition to find a complete set of extreme efficient solutions. Rather than using pre-determined weights or a dichotomic weighting approach, we present a procedure to identify the next weight to consider based on information obtained from the decomposed problem to obtain a complete set of extreme efficient solutions. This is applied to solve bi-objective two-stage multi-scenario stochastic linear optimization problems, in particular a capacity expansion network problem with multiple scenarios. Some numerical results will be presented.

3 - LocalSolver 11.0: Performance Improvements for Supply Chain Models

Thierry Benoist

LocalSolver is a global solver combining heuristic technics and exact search to quickly find good solutions and provide bounds. In previous versions LocalSolver introduced set and list decisions to easily model problems coming from the supply chain such as vehicle routing, production scheduling, packing. This talk will introduce the performance improvements coming with LocalSolver 11.0 released in early 2022. A list can be used to model the sequence of clients visited by a truck in a routing application. LocalSolver 11.0 focused on performance improvements for routing problem with time windows (CVRPTW, PDPTW). On classical instances from the literature, the gap to the best-known solution is reduced to less than 4% in one minute of running time for CVRPTW and less than 3% for PDPTW. List decisions can also be used to model scheduling problems and represent the sequence of tasks performed on a single disjunctive machine. LocalSolver 11.0 introduced a new heuristic search to quickly find very competitive solutions for scheduling problems. This new technic allows LocalSolver to have solutions with a gap to the best-known solution smaller than 5% for the jobshop scheduling problem and with a gap smaller than 1% for the flexible jobshop problem with or without setup times on classical instances in less than one minute.

4 - A Genetic Algorithm for the Multi-compartment Vehicle Routing Problem with Stochastic Demand and Flexible Compartment Sizes

Shabanaz Chamurally, Julia Rieck

In the multi-compartment vehicle routing problem (MC-VRP), supplies of different product types have to be collected from a set of customers and transported to a central depot. The problem consists of designing a set of routes to perform the collection of different product types from the customers with minimal costs. The MC-VRP arises in several practical situations such as selective waste collection or different colour of glass collection. Compartment sizes can be either set as fixed or as flexible. If flexible compartment sizes are used, the vehicles can be divided into multiple compartments. Often in practice, the collection quantity from customers is stochastic in nature, that is, the exact value is not available during route planning and is known only once the vehicles are at the customers' locations. Our work introduces the MC-VRP with stochastic customer demands and with flexible compartment sizes. We propose a Genetic Algorithm (GA) to solve this problem and investigate the benefits of setting the compartment sizes to be flexible instead of fixed with pre-defined sizes.

■ TB-19

Thursday, 10:00-11:30 - 20.30 SR 0.019

Behavioral Analytics

Stream: Analytics and Learning
Invited session
Chair: *Jochen Gönsch*
Chair: *Thomas Setzer*

1 - Analyzing customer shopping experience by AI power

Gozde Genc, Gizem Caliskan, Elif Aras

In the retail sector, employees work on such routine operations. In order to obtain shelf fulfillment, detect rotten fruit & vegetables, and prevent out of stock this project is developed. Besides, there is another important point which is analyzing customer behavior & shopping journey. In this scope, image recognition technologies in artificial intelligence solve our problem. The facts that are mentioned can be traced by the cameras that are positioned in the store. This project is conducted by Migros Research & Development Center. The studies that are done so far such as image recognition on store operations, literature review around 15 publications lead us to realize opportunities. The aim of this project is send to real-time notifications to store managers and share reports with related departments. Analyzing the

customer's behavior when they choose the product which they would like to buy from the shelf, by image recognition system gives us the result of decisions about ordering and which product on the shelf is preferred or not mostly. The literature studies show that the future is about focusing on the stated topics in this article. Thus, many sectors would improve their operations by working on this solution.

2 - Learning equilibria in double auctions via self-play

Nils Kohring, Fabian Raoul Pieroth, Matthias Oberlechner, Martin Bichler

The simplest form of double auctions and trade, in general, can be described by bilateral bargaining of a single good among one buyer and one seller. Nonetheless, equilibrium strategies in this scenario remain largely unknown. Only for the average mechanism in the simplistic independent private values model with uniform priors, do we know equilibria. However, a non-uniform prior distribution already leads to a system of non-linear differential equations for which closed-form bidding strategies cannot be derived. Recent advances in equilibrium computation provide numerical approaches to equilibrium analysis, which allow for the analysis of environments that have been considered intractable so far. These equilibrium learning algorithms include Neural Pseudogradient Ascent (NPGA) and Simultaneous Dual Averaging (SODA), which are specifically designed for Bayesian auction games with continuous type and action spaces. Although the environment is simple to describe, a known continuum of equilibria makes it challenging for equilibrium learning algorithms. We show that for the model with uniform priors, NPGA finds the payoff-maximizing linear equilibrium, while SODA also finds non-differentiable step-function equilibria. However, we can also go beyond and derive equilibrium bid functions for non-uniform priors, risk-averse traders, and markets with multiple traders on each side, which were impossible so far. Assuming uniform priors and linear bid functions, we can also illustrate the shape of the expected utility function and prove local convergence of NPGA in this environment, which provides a rationale for the empirical results we provide in the paper.

3 - A Decision Support System Including Feedback to Sensitize for Certainty Interval Size

Nathalie Balla

In decision-making humans are confronted with cognitive biases, which often lead to suboptimal decisions. This topic is of significance in behavioral operations research, as many decisions are made by humans, for instance in supply chains. A Decision Support System (DSS) that adapts to individual biases and combines the strengths of humans and machines is required.

We introduce such a DSS and report results of an experiment where subjects are asked to answer estimation questions from different categories, presumably easy to detect by subjects and supported by visual information. The subjects indicate an absolute value and a 90% certainty (confidence) interval. After a series of questions, a subject's Mean Percentage Error (MPE) is computed over the previous answers and displayed as feedback. Additionally, feedback on the certainty intervals indicating whether the correct answer lay within the given range is provided. After the feedback, subjects answer another series of questions of the same categories.

It is analyzed, whether the error structure and the certainty intervals change before and after the feedback. A subject's intervals are examined regarding size and the position of the correct answer within the interval before and after the feedback.

The expectation is that the MPE decreases and the intervals become more adequate after the feedback as the subjects reflect on the appropriateness of the previously given intervals and are nudged into the right direction. In case the intervals were too narrow and the correct answer did not lie inside the interval, indicating overconfidence before the feedback, they should become wider afterwards, meaning to reduce overconfidence and vice versa.

4 - ML2-Choice Based Optimization

Fiona Sauerbier, Knut Haase, Jannis Kück, Martin Spindler

Digitization leads to larger data sets available as input for optimization problems, in particular also for choice-based optimization problems which are usually combined with maximum likelihood estimation. Machine learning are particular useful for analyzing high-dimensional, complex data sets. With ML2 we denote the combination of machine learning and maximum likelihood estimation. We consider a high dimensional estimation problem and a location problem under the multinomial logit model. We integrate the machine learning methods Lasso regression and Ridge regression into the maximum likelihood method to estimate the multinomial logit model. We perform a computational study using synthetic data to determine the optimal solutions to location planning problems. The results are used to analyze the quality of the solutions of the location problems depending on the estimation method used.

■ TB-20

Thursday, 10:00-11:30 - 20.30 SR 0.016

Revenue Management for Air Transport and Production

Stream: Pricing and Revenue Management
Invited session
Chair: *Claudius Steinhardt*

1 - Booking Limits vs. Bid-Prices - A Comparison of Revenue Management Strategies for Make-to-Order Production

Nina Lohnert, Kathrin Fischer

Due to strong competition, there is a trend towards individualized products, leading to large numbers of product variants. To handle this situation, many companies apply the make-to-order principle where production only starts after an order has been accepted. However, due to limited capacity not every order can be fulfilled and hence, decisions regarding order acceptance have to be made. The objectives pursued by a manufacturing company in this situation are usually twofold: On the one hand, companies aim to maximize (short-term) profits. On the other hand, the goal of providing good service in particular to valuable, returning customers is crucial with respect to long-term business success. These two objectives are usually in conflict as valuable customers often get price discounts to tie them to the company. In this talk, booking limit and bid-price based revenue management strategies for order acceptance are presented and compared. Both strategy types use a two-stage acceptance process that combines two mixed-integer linear programming models. In the first stage, a preliminary acceptance decision is made by booking limits/bid-prices. In the second stage, subsequent production scheduling is considered to ensure that only orders are accepted which can be completed no later than their deadline. Moreover, aspired service levels for different customer groups are included in both models, to take not only the profit, but also the customer value into account. The performance of the different strategies is compared in various case studies, with the well-known first-come-first-served policy serving as a benchmark. It can be shown that the suggested revenue management strategies work successfully and are able to establish a good trade-off between the conflicting objectives.

2 - The value of flexible flight-to-route assignments in pre-tactical air traffic management

Arne Strauss, Jan-Rasmus Kuennen

To inform current discussions on the future role of the network manager in air traffic management, we illustrate the value of flexible flight-to-route assignments by dynamically influencing airspace users' choices by pricing decisions to make flexible options more attractive when needed; the overall aim is to reduce costs arising from reroutings, tactical delays, and penalties (for violating fairness and revenue neutrality conditions). This problem is structurally related to the last mile next day delivery problem but poses some special challenges.

3 - On the value of tracking booking data for upsell decision-making in airline revenue management

Davina Hartmann, Jochen Gönsch, Claudius Steinhardt

In airline revenue management, it is common practice to offer available seats in higher-value compartments at the end of the booking horizon as an upsell to customers with existing bookings in a lower compartment. For example, Economy Class customers are offered a seat in Business Class. The airline must decide which customers to offer an upsell to and at what price. In this paper, we address this decision problem and assume that the customers' original choice decisions in the booking horizon follows a multinomial logit model. We propose a probabilistic nonlinear optimization model, in which the customers' response probability is represented as a conditional probability formally consistent with their original buying decision. The core of the analysis is that we can use the solution approach to contrast different degrees of collected customer data from the booking process, which we term different states of information, such as knowledge about the original offer set provided or an estimate of the customer's segment. In an extensive

numerical study, we show to what extent the exploitation of customer-specific information is worthwhile for the provider. Sales increase significantly with knowing the customers' offer sets and the customer segments. Furthermore, the study shows that formal consistent modeling using the derived conditional probabilities yields considerably higher sales benefits compared to a presumably obvious independent modeling of the upsell response using a binary logit model.

■ TB-21

Thursday, 10:00-11:30 - 30.96 Seminarraum 1. OG (R104)

Single and Identical Machine Scheduling

Stream: Project Management and Scheduling
Invited session
Chair: *Klaus Jansen*

1 - A hybrid local search algorithm for the Continuous Energy-Constrained Scheduling Problem

Roel Brouwer, Marjan van den Akker, Han Hoogeveen

We consider 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 the total weighted 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), and for a given order determine optimal start and completion times as well as resource consumption using an event-based LP formulation. 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 piece-wise linear resource availability functions, explicit precedence relations and linear efficiency functions.

2 - Single Machine Scheduling Problems with Position Dependent Maintenance

Andreas Hipp, Florian Jaehn

In traditional machine scheduling, continuous machine availability is assumed over the whole planning horizon. But in fact, machine deterioration takes an important part in real-world applications. Therefore, we consider uniform machine deterioration caused by jobs and maintenance operations that have to be scheduled to recondition the original state of the machine. After performing a certain number of jobs, the wear and tear of the machine prevents the processing of further jobs and the execution of a maintenance operation is required. The length of maintenance operations is fixed and the deterioration of the machine only depends on the number of scheduled jobs, not on their processing times. This type of maintenance is called position dependent (pd). In real-world, this type of machine deterioration can be found in certain settings like dealing with the wear and tear of automotive batteries or landing gear of aircrafts. In our work, we examine classic completion time and due date based objective functions in single machine scheduling problems. After discussing the complexity of several single machine problems with pd maintenance and ready times, weights or job preemption, we focus on the case of minimizing the weighted sum of completion times under consideration of ready times and identical processing times for all jobs. We formulate a dynamic program to solve this layout optimally in polynomial time and apply the algorithm to a data set oriented on the testbed provided by Drozdowski, Jaehn and Paszkowski in 2016.

3 - On scheduling problems with recurring due dates in a personalized drug production

Raphael Kühn, Heiner Ackermann, Sandy Heydrich, Christian Weiß

We present a scheduling problem motivated by the production requirements of a pharmaceutical company that produces personalized medications. For treatment, patients are typically given one appointment per week. If the production process is not finished by the time of the first appointment, the appointment is not rescheduled and instead a later appointment is used to start administration of the drug. Thus, if an appointment is missed, it is not necessary to immediately hurry along the production for that specific patient, since it will be a week before the drug is needed again. In the meantime, the production for other patients can be prioritized. The goal is to miss as few initial appointments as possible, with missing later appointments incurring higher penalties. In scheduling terms, each patient is a job and each job has multiple due dates associated with it. In addition, each due date has a weight. The goal is then to minimize the total weight of missed due dates, i.e., the weight of those due dates which pass before their associated job is completed. Note that this is a generalization of the well-studied scheduling problem to minimize the weighted number of late jobs. Thus, in general, the problem is NP-hard to solve even on a single machine. We consider the single machine model with release dates and the special case where all jobs have equal processing time. If that processing time is unit, then we show that the problem can be solved in polynomial time as an assignment problem. Otherwise, we consider complexity results for several special cases and discuss heuristics for the general case. We also show how the results apply to the slightly more general production environment used by our industrial partner.

4 - 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 + epsilon)-approximation solution for every epsilon > 0, but the running time grows exponentially in 1/epsilon. For a long time, these schemes seemed like a purely theoretical concept. Even solving instances for moderate values of epsilon 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 epsilon lower than $2/11 \approx 18.2\%$ 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.

■ TB-22

Thursday, 10:00-11:30 - 20.30 SR -1.008 (UG)

Scheduling and Simulation

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *Benedikt Zipfel*

1 - A heuristic procedure for personnel task rescheduling with time-resource-quality trade-offs

Tessa Borgonjon, Broos Maenhout

In this paper, we consider the personnel task rescheduling problem with multiple dis- crete activity modes following time-resource-quality trade-offs. Due to operational uncer- tainty, announced baseline schedules may become infeasible and the need for reschedul- ing arises. To restore feasibility, changes are required to either the resource schedule or the service level impacting the task delivery. In this study, we explore in particular the recovery action to change the operation modes of individual activities, instigating a trade-off between time, quality and assigned resources. We propose a two-stage heuristic procedure targeted at finding high-quality solutions in an efficient manner. The first stage improves an initial schedule by exploiting different local improvement steps. The second stage merges different high-quality solutions via mathematical programming by combining task-worker assignment patterns identified in multiple visited schedules. The performance of the proposed procedure and the corresponding acceleration strategies is demonstrated by a range of computational experiments, benchmarking the two-stage procedure with other optimisation procedures and validating algorithm design choices. Furthermore, we evaluate the value of having the possibility to select one out of multiple operation modes for schedule recovery and the impact of different mode settings.

2 - Unreliable server Markovian queue with two-stage service process under hybrid vacation policy
Anshul Kumar, Madhu Jain

In this investigation, an unreliable server Markovian queueing model is developed for a service system by considering a two-stage service process and hybrid vacation policy. By including the features of combination of working vacation (WV) and complete vacation (CV), the steady-state probability distribution of the queue size of the two-stage service model via matrix geometric approach has been established. The cost function has been formulated to evaluate the optimal values of the decision variables of the service system. Particle swarm optimization (PSO) and Artificial bee colony (ABC) optimization algorithms are employed to perform the cost minimization in order to compute the optimal service rates at optimum cost. To validate the model, numerical illustrations along with sensitivity analysis have been provided. Finally, the conclusions and future scope of the investigation are drawn.

3 - Coopetition and knowledge sharing in dynamic business environments
Ayesha Alhosani, Richard Allmendinger, Mercedes Bleda

Strategic alliances represent groups of complementors/competitors and are increasing in popularity in management as organizations recognize the benefits of being part of an alliance. Nowadays, organizations not only cooperate with their complementors but also with their competitors in a phenomenon known as "coopetition". Therefore, it is crucial for organizations to understand how to reap the most benefits from being in an alliance by learning from each other and sharing knowledge among partners.

In this work we use multi-agent simulation coupled with principles from operations research to study how learning and knowledge sharing among alliance members can impact the performance of firms in an environment consisting of two types of firms: ones that only search the fitness landscape (searchers) and ones that search and have the power to reshape the business landscape to their advantage or others' downfall (shapers). Thus, the presence of shapers leads to a dynamic environment by causing an endogenous change to the business landscape and forcing other firms to adapt to the change. In this model, members (firms) of an alliance collaborate and have a shared knowledge base meaning they communicate their expertise with other alliance members.

Overall, our work demonstrates that principles from operations research, multi-agent systems, and behavioral science have a role to play in discovering how businesses may want to adapt and collaborate most effectively in these complex business environments. Moreover, it is realistic and informative to assume that businesses can use such advanced forms of cooperative learning to remain viable in the face of endogenous environmental changes.

4 - Low Budget Traveling: The Orienteering Problem with Hotel Selection and Budget Constraint
Paul Päprer, Benedikt Zipfel

The orienteering problem with hotel selection (OPHS) considers the planning of multi-day tours with consecutive trips aiming to maximize the total score of the tour. Initially, the problem was motivated by tourists' travel planning, who had to decide which attractions they wanted to visit on their vacation. Having limited time, the tourists try to include as many points of interest as possible in the itinerary. Apart from this classical application, the problem can be applied to other decision problems like routing for maintenance technicians or truck drivers.

We introduce an additional cap on the available budget frequently experienced in practice but neglected in the literature. We refer to this variant as the orienteering problem with hotel selection and budget constraint (OPHSBC). We present a heuristic solution approach for the modified problem configuration, which comprises the construction of initial solutions and improving those solutions using a multi-start VNS heuristic with adaptive adjustment. While the focus of the constructive phase is on generating promising hotel sequences, the improvement phase subsequently addresses the problem of finding the best possible tours between the specified hotels.

Within computational studies, we analyze the impact of the considered budget constraint by comparing the results of the original OPHS with the results of the OPHSBC. Therefore, we use test instances of the existing OPHS benchmark dataset and adjust them by our extensions. We show the efficiency of the proposed metaheuristic and evaluate the impact of budget variations on the total score within a sensitivity analysis.

Thursday, 12:45-14:15

■ TC-04

Thursday, 12:45-14:15 - 10.11 Hertz-Hörsaal

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 Gustav Feichtinger 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.

■ TC-05

Thursday, 12:45-14:15 - 11.10 Engelbert-Arnold-Hörsaal (EAS)

Agrifood and Semiconductor Supply Chains

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

1 - Impact analysis of extended payment terms in food supply chains during a demand shortfall
Alexander Zienau, Ole Hansen, Christina Imdahl, Mahdi Alazzeh, Marcus Wiens, Frank Schultmann

In response to supply and demand disruptions during the COVID-19 pandemic, companies with high bargaining power extended their own payment terms. This may increase their available capital in the short-term but can harm long-term supply chain performance. In food supply chains with low profit margins and few companies with concentrated bargaining power downstream, the financial equilibrium is especially fragile. Insufficient funds at upstream suppliers can hamper production and thus endanger food supply. A countermeasure is the Directive 2019/633/EU which limits payment extensions in food supply chains. Although the COVID-19 pandemic has revealed the relevance of the topic, little research has been done on the impact of extended payment. For a stylized multi-echelon food supply chain consisting of supplier, manufacturer and wholesaler, we develop a model in which physical flows are designed to meet the downstream service level with a (s,S) order policy. We evaluate financial flows using each echelon's cash conversion cycle. Inspired by lockdowns during the COVID-19 pandemic, we simulate how a shortfall of demand in gastronomy and payment extensions of upstream companies impact supply chain performance. We analyze the outcome for payment extension of wholesaler and manufacturer, different durations of extended payment and different degrees of market power for manufacturer and supplier. All these settings determine if and how much the company extending its payment suffers from supply disruptions. Our study enables researchers and practitioners to analyze the interplay between physical and financial supply chain flows in crises and to evaluate corporate decisions about an extension of payment. It can also serve as decision support for public actors.

2 - Procurement and production planning for horticulture with consideration of short-term re-orders
Marius Drechsler, Andreas Holzapfel

For small and medium-sized enterprises in the horticultural business, the procurement and production planning of ornamental plants, perennials and cut flowers constitutes significant challenges. Lead and production times of several months, as well as distinctive seasonality and high perishability of the products have to be considered. Reflecting

these challenges, companies usually distinguish between own production or pre- and re-orders. Own Production as well as pre-orders with several months of lead time before the start of the selling season guarantee a basic availability and sufficient quality. Re-orders during the selling season have at most a few weeks of lead time and thus offer short-term flexibility, but are uncertain and fluctuate in price and quality. We present a stochastic procurement and production planning model reflecting these conditions. A MILP approximation provides production/pre-order quantities and estimates necessary re-order quantities for the selling season.

3 - Data-driven prediction of order lead time in semiconductor supply chain

Xin Shen, Patrick Moder, Christian Pfeiffer

In the digital era, semiconductors are witnessed as inevitable components to drive digital transformation. Competitive order lead times enable increased customer experience and high profitability for the semiconductor business since they are a crucial indicator highlighting the overall supply chain performance. Downstream manufacturers expect a reliable order lead time and its transparent communication to hedge against unpredictable risks. Recent studies concerned with lead time estimation use methods such as classical queueing theory or operating curves that have limitations in the dynamic and unsteady operating environment. Further, simulation approaches lack generalization due to incomplete input information and (over)simplified modeling. Unlike preliminary work, this study proposes an AI-empowered order lead time prediction integrating a multidimensional real-world dataset from a semiconductor manufacturer's supply chain. Examined features capture order-, delivery-, planning-, customer-, and product-related information. We thoroughly analyze a broad spectrum of machine learning algorithms ranging from linear regression and tree-based machine learning models to neural networks and compare them with respect to accuracy, computation time, and understandability. The boosting algorithms demonstrate solid predictive performance with the highest accuracy and most efficient computation time. We find that the business cycle (ramp-up date) and planning parameters (cycle time and freeze fence) inform the prediction models aside from certain order specifics. Our results allow supply chain experts to obtain data-informed estimations of order lead times and an understanding of the predictive performance.

4 - Mitigating the Chip Shortage after Disruptions with MPC (Multi-Party Computation) to Reduce the Bullwhip Effect - a Discussion Contribution

Philipp Ulrich, Hans Ehm

Accurate demands are integral for the semiconductor industry to ensure the optimal setup of production and achieve demand fulfillment and customer satisfaction. Disruptions like the pandemic challenge estimation of demand by introducing high variability. Furthermore, the Bullwhip Effect, an amplification of demand along supply chains, intensifies changes drastically. Supply chains in automotive rely on just in time from the OEM's point of view and are commonly steered according to reach, which acts as another Bullwhip accelerator, especially with disruptions. More demand transparency and collaboration are means to mitigate the Bullwhip Effect sustainably but are hindered by a reluctance to share sensitive information with other tiers in supply chains. Companies often communicate inflated tactical demands to the semiconductor manufacturers in crisis situations to ensure their deliveries which introduces further bias. As a result, semiconductor companies are unable to plan optimally which leads to the ongoing worldwide chip shortage.

A solution is to remove the incentive for communicating tactical demands in an anonymous true demand survey. Such a survey doesn't rely on trusting a third party but is anonymous on a technical level enabled by Multi-Party Computation (MPC). The anonymity removes the incentive to communicate a tactical demand since demand information shared through the survey is not used for ordering. Furthermore, complexity can be handled with Semantic Web and simulations investigating game-theoretical aspects. Results of the survey are securely aggregated and averaged afterward and enable all survey participants from the tiers OEM, Tier 1, Tier 2, and others to get a better overview of the supply chains' state and deduce further own actions.

■ TC-06

Thursday, 12:45-14:15 - 10.91 Redtenbacher-Hörsaal

Decision Analysis for Environmental Management

Stream: Decision Analysis and Support
Invited session

Chair: *Fridolin Haag*
Chair: *Lisa Scholten*

1 - Multi-Actor Multi-Criteria Analysis for Transboundary Integrated Water Resources Management Infrastructure Projects in the Middle East

Sebastian Schär, Jutta Geldermann

Population increase, growing urban areas and the effects of climate change impose great challenges on decision-makers to identify efficient, sustainable and accepted measures for water stress mitigation, especially in arid regions. Decision analysis can aid to tackle these challenges by evaluating possible measures while considering multiple, conflicting objectives and by allowing stakeholder integration and participation at all levels of the decision process. Furthermore, decision-making in this context is not bound to the national scope. Often times, countries share natural resources or interests and are engaged in transboundary arrangements and thus simultaneously affected by the consequences of decisions and, moreover, even reliant on reaching consensus in case of transboundary infrastructure projects. Within the decision support process, this sets special requirements on method selection, problem structuring and model formulation in order to adequately consider all interests, interdependencies and to foster a common understanding of the decision problem at hand. We present a decision problem to rank integrated water resources management infrastructure projects in Israel, Jordan and Palestine to identify the most preferred water production and transfer strategy. The projects are assessed based on sustainability assessment criteria within the ecological, economic, social, technical and political domain, using the Multi-Actor Multi-Criteria decision-making method and PROMETHEE methods for evaluation. This approach allows to explicitly consider diverging stakeholder objectives in the evaluation and to identify and highlight aspects which are responsible for possibly divergent assessments between the stakeholders, engaging the process of consensus building.

2 - Which uncertainty to resolve? Analyzing the value of information for environmental decisions

Fridolin Haag, Arjun Chennu

Uncertainties in environmental decisions are large, but resolving them is costly. This requires a targeted approach to data and information collection. Value of information (VoI) analysis is a type of sensitivity analysis that supports identifying the key uncertainties in a decision. However, the characteristics of environmental problems make applying the VoI concept challenging. We address three characteristics: (1) the predicted outcomes of decision alternatives are uncertain, but their distributions are not independent; (2) stakeholder can have complex preference structures over multiple objectives; (3) not only the predicted outcomes but also preferences are uncertain. For a coral reef fisheries case study, we predict trajectories of the ecosystem and the fisheries given different management alternatives with an agent-based model. We evaluate the uncertain predictions with preference models for several stakeholders. Since preferences are uncertain, the expected utility concept is insufficient for finding optimal alternatives. Instead, we use the extension provided by the expected expected utility concept. The decision's sensitivity to new information can be measured by the expected value of partially perfect information (EVPPI). To estimate the EVPPI, we implement an efficient algorithm that only requires a single loop Monte Carlo sample. The resulting ranking of uncertainties allows us to compare preference and prediction uncertainties on an equal footing. The value of added information is often not greatest for parameters with the highest variance. Our approach helps to make structured decisions iteratively and reduce costs by prioritizing data collection efforts for the key decision uncertainties.

3 - UrbanLemma: A serious game to support adoption of sustainable urban drainage solutions

Aashna Mittal, Lisa Scholten, Zoran Kapelan

Long-term planning of urban drainage systems (UDSs) is required to prevent pluvial flooding and help with addressing droughts, especially given the challenges of climate change, increasing urbanization and

population growth. This involves making decisions about how to upgrade the existing UDS so that future long-term goals are met. Sustainable urban drainage systems (SUDS), e.g., permeable pavements, or rainwater harvesting systems are increasingly used to manage water and build resilience in urban environments. However, the adoption of these solutions by stakeholders remains low due to various barriers such as lack of knowledge, and reluctance to support new approaches. Models to understand environmental behaviors such as Schwartz's Norm Activation Model posits that pro-environmental actions follow from the activation of personal norms which are influenced by problem awareness and ascription of responsibility. Serious games are a promising solution to improve problem awareness as they provide an immersive and engaging platform that can be used to educate, teach skills, motivate, and improve decision-making. Furthermore, they are gaining popularity as a means to address urban water management problems. However, their potential to change norms and attitudes, thereby influencing behaviors pertaining to adoption of SUDs has not been investigated so far. This paper presents the proof-of-concept of a serious game UrbanLemma, designed to increase awareness of consequences of SUDs and the responsibility of actors involved in UWM, with the aim to influence the stakeholders' personal norms. Initial results from play-test sessions conducted with students and researchers at TU Delft are presented and lessons learnt from the game development process are discussed.

■ TC-07

Thursday, 12:45-14:15 - 10.91 Grashof-Hörsaal

Decision Support in Practise

Stream: Decision Analysis and Support
Invited session
Chair: *Philipp Süss*

1 - Rather the rule than the exception: Non-convex Pareto sets in flowsheets from chemical process engineering

Michael Bortz, Norbert Asprion, Dimitri Nowak, Katrin Teichert

The chemical industry is one of the leading industries in Germany and, at the same time, one of the major energy consumers. However, due to the complexity of the production processes and due to conflicting objectives, potentials for energy savings are hard to be identified. Therefore, simulation and multicriteria optimization are used, which are based on physical models represented by large nonlinear systems. In this contribution, novel algorithms for the adaptive approximation and interactive navigation of Pareto sets are applied to different homogeneous distillation processes with recycle streams within an industrial flowsheet simulator. The adaptive approximation scheme shows that when maximizing the product purities while minimizing the total heat duties, the Pareto set consists of both convex and non-convex regions. It is illustrated how such Pareto sets can be navigated interactively by using a ray-tracing technique. Our findings suggest that the appearance of non-convexities in the Pareto sets is due to recycle streams in the flowsheets and thus can be considered rather the rule than the exception in multicriteria optimization of flowsheet simulations in chemical engineering.

This talk will be held by two speakers, one from industry (Norbert Asprion from BASF) and one from a scientific institute (Michael Bortz from Fraunhofer ITWM).

2 - QRITOS: Product development in a multicriteria context with the customer in mind

Philipp Süss, Gregor Foltin, Melanie Heidgen, David Hajnal, Jorge Diaz, Hergen Schultze, Jochen Gattermayer, Stefan Lehner

We understand product development to be the task to find a synthesis and formulation of ingredients that result in a marketable commodity. Being successful on the markets depends on many criteria: the application properties need to match specifications, the production costs need to be low and the carbon footprint needs to be low as well - just to name a few. ITWM and BASF have developed the QRITOS workflow that allows data scientists and technical staff to easily prepare ready-to-explore Pareto fronts for product development and customer engagement.

QRITOS is a collaborative decision-making tool intended to assist product developers, technical service and customers in multi-criteria decision-making. Users can virtually configure their product in real-time using by interactive sliders depicting objectives of the design. QRITOS then determines efficient trade-offs for wishes users make. This Pareto Navigation has been previously applied successfully in radiation therapy planning and in various process design applications. New in the QRITOS suite is (i) the purely data-driven modelling of the optimization problem using only recorded laboratory experiments, and (ii) its intended use not by data scientist experts at BASF but their internal business partners and external customers themselves.

3 - Finding the best radiotherapy treatment by interactively navigating the Pareto front

Katrin Teichert, Ina Lammel, Philipp Süss

In radiotherapy treatment planning, the aim is to find the patient individual best compromise between irradiating the target as completely as possible and sparing nearby organs at risk. Over the last decade, interactive navigation has been introduced in clinical practice as a powerful decision support tool that enables clinicians to find the best treatment plan in a reliable and time-efficient manner. In our contribution, we extend the navigation concept to mixed integer MCO problems. For radiotherapy planning, this allows for the integration of discrete choices such as particle type, machine type or beam configuration into the interactive decision making. We discuss prerequisites regarding the Pareto front approximation to facilitate our new approach, and then demonstrate how the established user interactions employed in interactive navigation - namely selection and restriction - can be adopted to handle discrete variables. We also present novel routines and visualizations that are specifically geared towards deciding between discrete options. Finally, we show that our approach can be successfully applied to a realistic treatment planning problem.

■ TC-08

Thursday, 12:45-14:15 - 10.50 HS 102

Optimal Power Flow Problems and Solution Methods II

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *John Warwicker*

1 - A Generalised Approach for Efficient Computation of Look Ahead Security Constrained Optimal Power Flow

Lamia Varawala, György Dán, Mohammad Reza Hesamzadeh, Ross Baldick

We consider a generalised comprehensive Look-ahead Security-constrained Optimal Power Flow (LASCOPF) formulation under the N-1 contingency criterion over multiple dispatch intervals. We observe that the number of decision variables varies quadratically with the number of intervals. To improve scalability, we propose a reduced LASCOPF formulation for which the number of decision variables varies only linearly. We extend these formulations to the N-k contingency criterion. For reduced LASCOPF we observe that the number of decision variables varies with the number of k-permutations of contingencies. To improve scalability, we propose a formulation that is further reduced to vary only with the number of k-combinations. Also, we show that our formulations can be extended simply to model recovery from the corresponding outages. Furthermore, we present LASCOPF under the N-1 contingency criterion using DC and AC power flow under generator contingencies. We prove that, barring borderline cases, solving the reduced formulation is equivalent to solving the comprehensive formulation. We extend these results to the N-k contingency criterion. Finally, we present numerical results on the IEEE 14 bus, IEEE 30 bus, and 2383 bus Polish power systems using AC power flow to demonstrate the computational advantage of the reduced formulations under the N-1 and N-2 contingency criteria.

2 - Linearised Optimal Power Flow Problem Solution using Dantzig - Wolfe decomposition

Giacomo Bastianel, Hakan Ergun, Dirk Van Hertem

The optimal power flow problem can be used to determine the generation dispatch in electrical grids taking into account circuit physics and technical constraints. This paper provides exploratory work on solving the OPF problem using Dantzig-Wolfe reformulation (DW), applying it to the linearised 'DC' OPF approximation. In order to test the developed method, three examples of small power systems are chosen and the computational performance is validated against existing optimal power flow tools, e.g. PowerModels.jl, using commercial LP solvers. The goal of the DW decomposition is to express the polyhedron of the original problem as a combination of extreme points Q and extreme rays R. Each feasible set is represented as a multitude of vertices in the solution space linked by extreme rays. The OPF problem after DW decomposition is based on two subproblems respectively linked to the set of generators and branches in the power system. The complicating constraints consist of the nodal balance and power flow equations. A column generation (CG) algorithm is developed. The Master Problem (MP) is reduced to a restricted master problem (RMP) where only a small subsets of vertices is updated for each iteration of the CG algorithm to improve the computational speed. The CG algorithm determines the columns of variables to be added by combining the objective value of the subproblems with the simplex method. These columns are generated for each iteration of the optimization process, providing a solution where selected vertices from the feasible sets are assigned a weight and combined to get the optimal value. The results of the three test cases consist of an useful starting point for further work with larger test systems and MILP problems such as the TNEP problem.

3 - A Tabu Search Approach to the Short-Term Operational Planning of Power Systems

Ionela Knospe, Roman Stainko, Anna Gattinger, Michael Boegl, Katharina Rafetseder, Dominik Falkner

The accelerating transition towards clean energy is raising the need to consider electric power systems with an increased integration of renewable energy sources, energy storage systems (ESS) and flexible loads, in addition to the classical programmable generators (PG) and electricity demand. Within this setting, we consider the optimal short-term operational planning of power systems with a quarter-hourly time resolution and with the objective of minimizing its total operating cost. This Unit Commitment Problem considers the technical details of the generation units, and the transmission grid constraints are implemented with a DC power flow model. The electricity demand and photovoltaic production data is provided by forecast models that are based on historical and real-world data sets.

Our approach for solving this optimization problem is a hierarchical approach based on Tabu Search with adaptive neighborhood operator selection. More precisely, in each iteration we determine first the commitment status of the PG and ESS units for the entire planning horizon. With the obtained commitment status of the ESS units, we solve an LP problem over the entire planning horizon for computing the optimal ESS charging and discharging power levels. Finally, with the commitment of the PG and ESS units and the ESS dispatch levels, a DC-OPF problem is solved for each time step in the planning horizon to obtain the optimal power generation of the PG units. A free solver is used for solving the ESS optimal dispatching and the DC-OPF problems.

4 - Chance constrained DC optimal power flow with discrete curtailment of renewables

Kevin-Martin Aigner, Jan-Patrick Clarner, Frauke Liers, Alexander Martin

We propose a mathematical optimization model and its solution for joint chance constrained DC Optimal Power Flow. In this application, it is particularly important that there is a high probability of transmission limits being satisfied, even in the case of uncertain or fluctuating feed-in from renewable energy sources. In critical network situations where the network risks overload, renewable energy feed-in has to be curtailed by the transmission system operator (TSO). The TSO can reduce the feed-in in discrete steps at each network node. The proposed optimization model minimizes curtailment while ensuring that there is a high probability of transmission limits being maintained. The latter is modeled via (joint) chance constraints that are computationally challenging. Thus, we propose a solution approach based on the robust safe approximation of these constraints. Hereby, probabilistic constraints are replaced by robust constraints with suitably defined uncertainty sets constructed from historical data. The ability to discretely control the power feed-in then leads to a robust optimization problem with decision-dependent uncertainties, i.e. the uncertainty sets depend on decision variables. We propose an equivalent mixed-integer linear reformulation for box uncertainties with the exact linearization of bilinear terms. Finally, we present numerical results for different test cases from the Nesta archive, as well as for a real network. We consider the discrete curtailment of solar feed-in, for which we use real-world weather and network data. The experimental tests demonstrate the effectiveness of this method and run times are very fast. Moreover, on average the calculated robust solutions only lead to a small increase in curtailment, when compared to nominal solutions.

■ TC-09

Thursday, 12:45-14:15 - 10.50 Raum 604

Electricity market modelling

Stream: Energy and Environment, sponsored by EnBW

Invited session

Chair: *Dogan Keles*

1 - Risk-averse producers and consumers having storage and hedging contracts in energy market equilibria

Sining Liu, Martin Densing, Giovanni Sansavini

We analyse the role of storage in multi-period risk-averse energy market equilibria. In particular, we consider market agents who are energy producers or consumers with their objective to maximise profits. Each agent is price-taking and optimises under endogenous prices. The agents have storage facilities and are allowed to hedge their risk by trading futures contracts. To keep the model analytically and numerically tractable, we consider the decision making on a scenario tree where uncertainty unfolds over time. We use coherent risk measurement to model risk aversion which is represented by time consistent risk-adjusted values recursively defined over the tree paths, and the equilibrium is the combined optimisation of all agents together with the complementarity conditions of the energy spot and futures markets. We derive an explicit relation through agents' optimality conditions which describes the dependence of storage cost and storage availability on futures and spot prices. The relation can be interpreted as different market situations that relates to the conventional theory of storage. We construct the model in with hydropower storage in mind but it is general enough to be extended to other storage types.

2 - Volatility and flexibility of representative electric vehicle fleets: modeling electricity market implications

Jarusch Müßel

The electrification of the mobility sector plays a crucial part in fighting climate change. Growing numbers of electric vehicles (EVs) will increase the electricity demand substantially, thereby introducing volatility into the power system. However, EVs can potentially balance the power system by providing flexibility through system-friendly charging strategies. Charging data is key to assessing load shift or physical storage potentials. This study builds on sampled synthetic load profiles of single EVs based on national mobility data that account for behavioral patterns of different user groups. To make use of single-unit profiles in energy systems or electricity market modeling, the profiles must be aggregated to a fleet profile. Recent research has shown that naive aggregation results in an overestimation of the fleet's flexibility potential. In addition to a systematic comparison of charging profile generation models, this paper describes, visualizes, and assesses the aggregation error in detail. Then, a scalable and accurate solution to the aggregation problem is presented that allows for aggregating any amount of heterogeny profiles without losing accuracy. The approach is applicable for practical EV fleet management and aggregating variable flexibility sources in electricity market modeling. Thus, it is a strong foundation for assessing flexibility potentials in large-scale system analysis.

3 - Optimal operation and planning of a Multi-Carrier Microgrid including P2X on multiple electricity markets

Ioannis Kountouris, Lissy Langer, Dogan Keles, Marie Münster

The conversion of excess renewable electricity into hydrogen via water electrolysis as well as the synthesis of further energy carriers (e.g., liquid fuels) and other biogenic elements such as CO or CO2 creates new business opportunities and alternate revenue streams. Those energy systems known as Multi-Carrier Microgrid P2X systems (MCMG) are

projected to scale up their infrastructure in a couple of years. In this study, we investigate the optimal operation of an MCMG by utilizing the flexibility of P2X and other assets (i.e., electrolyzers, battery energy, and compressed hydrogen storage systems) and analyze the MCMG participating in different electricity markets such as the spot and the ancillary service market. The proposed optimization model performs a profit maximization considering the technical and physical constraints of the P2X assets given a variety of operational strategies and fulfilling the synthetic fuels demand. The model is presented and validated using a case study of the Danish industrial park GreenLab Skive. Preliminary results of the investigation underscore the benefits of exposing the renewable and P2X assets to both the spot and the ancillary service market.

■ TC-10

Thursday, 12:45-14:15 - 20.30 SR 0.014

Clustering and distribution problems

Stream: Logistics
Invited session
Chair: *Xuefei Yang*

1 - Machine Learning to Speed Up Solution Methods for the Joint Order Batching and Picker Routing Problem

Stefan Bomsdorf, Michael Schneider, Murwan Siddig

The Order Batching Problem (OBP) is the problem of grouping multiple customer orders into distinct batches while complying with the capacity restriction of a picking cart. The Single Picker Routing Problem (SPRP) aims to find a minimum-cost tour, visiting all picking positions within a picking order. The Joint Order Batching and Picker Routing Problem (JOBPRP) integrates both decisions and is NP-hard in the strong sense (see Gademann and Velde, 2005). We introduce machine learning techniques of regression to estimate the cost of optimal SPRP solutions. We use the estimates within the Adaptive Large Neighborhood Search and Tabu Search (ALNS/TS) introduced by Žulj et al. (2018) to solve the JOBPRP. To this end, we adapt the ALNS/TS to consider estimates instead of exact solution costs, and we propose a combined use of both to find the best quality-runtime tradeoff.

2 - Using Unmanned Aerial Vehicles in Last-mile Deliveries

Jeanette Schmidt, Christian Tilk, Stefan Irnich

Delivering packages in urban areas is becoming increasingly difficult. Not only high traffic congestion and strict parking regulations pose major challenges for carriers. They also have to deal with restrictions imposed by urban development and environmental policies.

One possibility to deal with these challenges is to integrate alternative transportation modes, like unmanned aerial vehicles (so-called drones) into classical freight flows. Compared to regular trucks, drones are not tied to the street network, can operate faster, and are more environmental-friendly than trucks. On the other hand, their loading capacity and flying range are much more limited than those of the trucks. To combine the advantages of both trucks and drones we consider a Vehicle Routing Problem, where each truck is equipped with a drone. 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) from the truck to serve a customer and meet the truck again before its flying range is reached. The overall goal is to minimize the total routing costs that consist of the routing costs of trucks and drones.

To solve the problem, we present a branch-and-price algorithm. The resulting pricing problem is a shortest-path problem with resource constraints that is solved with a labeling algorithm on an auxiliary network. We present computational results on CVRP benchmark instances.

3 - Line-TSP with a Drone

Anna Katharina Janiszczak, Stefan Bock

The analyzed problem is the Line-TSP with one drone. This problem consists of customers placed on a line, a truck and a drone delivering to those customers. The drone and the truck start their tour at the same fixed place on the line. Each customer has a time window and the drone can always serve exactly one customer after the truck and drone have met. The drone and truck can meet at any place on the line. The objective is to have the drone and truck meet as soon as possible after all customers have been served. Some special cases are polynomially solvable, whereas the problem is NP-hard if the time window constraint is removed and the drone is faster than the truck. This can be shown with a reduction of the Even-Odd partition problem. If only release dates or only deadlines are given, then the problem is NP-hard in the strong sense. Scheduling problems with start-time-dependent processing times are used for the reductions.

4 - Network Planning with Micro-fulfillment Centers for Quick Commerce

Xuefei Yang, Alexander Hübner, Manuel Ostermeier

With the rise of online grocery, new players are entering the market by offering same-day andup to same-hour delivery to their customers. Due to the requirement of such short lead-times,these online retailers need to further optimize their distribution network. Centralized warehouseshave limitations to fulfill quick commerce orders. Micro-fulfillment centers are an more and moreused option to shorten the last-mile distances to customers. We introduce the related networkplanning problem. The objective function minimizes total costs by taking into account operatingand transportation costs to fulfill customer orders. We develop a specialized heuristics that isbased on a MIP and an efficient approximation of the tour costs. We apply numerical examples togenerate insights into when and how to integrate micro-fulfillment centers into distribution systems.

■ TC-11

Thursday, 12:45-14:15 - 10.50 Raum 602

Revenue Management for Electricity Markets

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Jochen Gönsch*

1 - Coordinated bidding of grid connected multi-product charging station in electricity markets

Farnaz Sohrabi, Mohammad Rohaninejad, Mohammad Reza Hesamzadeh, Július Bemš

In recent years, there has been an urgent tendency to steer the transport system towards zero-emission. Along natural gas vehicles, which are playing a transitional role, the electric and hydrogen vehicles represent a promising and highly likely way to such a system. Since the development of these vehicles relies on advances of refueling stations, their economic and operational aspects need to pay more attention than ever before. This paper therefore addresses a multi product charging station which consists of a battery storage, electrolyzer, hydrogen tank, fuel cell and methanation system for refilling electric, hydrogen and natural gas vehicles at the same time and location powered by electricity grid. The station participates in the day-ahead and intra-day markets where the market price is subject to uncertainty. For charging station participating in sequential markets with different prices, it is relevant to consider the coordinated bidding. In both markets, clearing prices and dispatched volumes are unknown at the time of bidding. Taking into account the sequential clearing of these markets and the gradual realization of market prices, the bidding problem is formulated as a multi-stage stochastic program. The station aims to attain the optimal operation of the devices and bidding curves of the charging station in order to maximize the profit of the station. Finally, the economic effectiveness of the proposed multi-product charging station in different scenarios will be analyzed.

2 - An Evolutionary Algorithm for Bidding Strategies of Linked Block Orders in Day-Ahead Power Markets

Mehdi Sharifyazdi, Matin Bagherpour, Erlend Anfinsen, Moritz Georg Klauser-Baumgärtner

In many European countries, as well as some other regions of the world, a large share of wholesale electrical energy spot prices is determined in day-ahead markets, where power generators and power distributors place their bids for selling and purchasing electrical energy for the next day. The most common products (orders) traded in such markets are single hourly orders. At the same time, other forms of products are defined to create greater potential for the market participants, including Linked Block Orders (LBOs), which are among

the more complex and often underutilized bidding products for power trading. LBO bidding across power generating companies (GenCos) reflects a disparity in techniques and bidding outcomes. This paper analyzes the current state of LBO bidding using data from 13 European GenCos. Consequently, a method is proposed for creating LBOs that combines an evolutionary algorithm with a local search algorithm. The model is applied to the case of a Norwegian hydropower GenCo. Alternative LBOs are created by using the proposed method and subsequently compared to the GenCos' LBOs. Through retrospective comparisons on historical data, the authors find that substantially different LBOs achieve presumably better bidding outcomes than the historical practice of the GenCo in terms of profits.

3 - Energy-aware production planning in hybrid energy systems: A two-stage optimization approach

Thomas Volling, Kristian Bänsch

The substantial amount of energy consumed through industrial production has given rise to a large number of research papers that incorporate environmental aspects and energy-awareness into production planning. We present the results of a systematic literature review that classifies relevant papers and identifies open research areas. One of these open research areas considers the trade-off between energy costs and personnel cost: energy-aware production schedules are often fragmented and therefore impose challenges on shift planning. The consequence are rising personnel costs, which could more than absorb energy cost savings. One possibility to mitigate this trade-off is the implementation of on-site hybrid energy systems (HES). HES integrate technologies for energy generation and storage into industrial sites and open up a multitude of new options to facilitate environmental friendly production processes. We investigate the potential of HES in industrial production using a two stage mixed integer scheduling model that is able to optimize energy and personnel cost simultaneously. In the first stage energy, shift and production plans are optimized sequentially for each week of a year. In the second stage shift and production variables are fixed and the energy system is re-optimized for the whole year. A production environment consisting of unrelated parallel machines is considered. Energy demand can be covered by self-generation from solar and wind power, the use of a fuel cell or grid access under a time-variable tariff. Excess energy can be stored in the form of hydrogen via electrolysis or sold back to the grid. Start-up and production processes require personnel who can be scheduled in fixed shifts times. A numerical analysis shows promising results.

■ TC-12

Thursday, 12:45-14:15 - 10.50 Raum 701.3

Mobility and Traffic

Stream: Mobility and Traffic
Invited session
Chair: *Marjan van den Akker*

1 - Bidirectional Green Waves for Major Road Axes By Adjusting Separate Left-Turn Phases

Christian Liebchen

Planning so-called green waves along major road axes is a well-established target for traffic engineers. This is mainly for two reasons: a smooth traffic flow quality, and less air pollution. For one-way road axes (e.g., the Avenues in Manhattan), this is a trivial downstream task. For bidirectional arterials, there is a well-known necessary condition for establishing a green wave in both direction: The driving times between two subsequent crossings must be integer multiples of half of the cycle time of the signal programs at the nodes. In this presentation, we propose an integer linear optimization model to establish fixed-time green waves in both directions that are as long and as wide as possible, even in the situation where the above-mentioned driving time condition is not fulfilled. In particular, we are considering an arterial along whose nodes separate left-turn signal groups are realized. In our computational results, we show that scheduling left-turn phases before or after the straight phases can reduce waiting times along the arterial. Moreover, we show that there is always a solution with green waves in both directions that are as long and as wide as possible, where absolute priority is put on just one direction. Only when considering prioritized parts of a green band (e.g. some first few seconds), then an ideal green wave into one direction can provide suboptimal quality compared to optimizing both directions together. Finally, we validate the nominal solution quality according to the objective function values with the results of corresponding runs of the well-established traffic flow simulation tool SUMO.

2 - Routing electric cargo bikes: a hybrid solution approach

Marjan van den Akker, Sam Casper Hesselmans, Han Hoogeveen

Cities are getting more and more congested and environmental impact is becoming a larger point of interest for both customers and companies. Because of this more delivery companies are choosing to use cargo bikes instead of vans for the last mile delivery of packages. This brings an interesting challenge as most vehicle routing problem solutions are created with vans in mind. We study the vehicle routing problem for electric cargo bikes. Cargo bicycles differ from vans since they have less power and a lower weight. Because of this, the difference in travel speed caused by the weight of the load and also by the slope of the road is significant for cargo bicycles, whereas this is negligible for vans. Hence, load dependent travel times have to be taken into account when we want to find a good routing solution. Specifically, we consider the vehicle routing problem with load-dependent travel times for cargo bicycles (or VRPLTT) as proposed in an earlier paper by Fontaine. This problem is a variant of the capacitated vehicle routing problem with time windows using a single depot. Our contribution is twofold. Firstly, we present a hybrid solution method based on combining column generation and local search. This method was introduced by Ten Bosch, Hoogeveen and van Kooten Niekerk for scheduling of electric buses, and as far as we know, new. We show that we can improve the solutions by applying this method. Secondly, in the original model, travel times are deterministic. This might not be a correct representation of the real world as, especially in the city, travel times are not deterministic. Therefore, we show how to include stochastic travel times in our solution algorithm for VRPLTT and present computational results based on real-life instances.

3 - Evacuation based extension of the System Optimal Dynamic Traffic Assignment Problem

John Micha Rüpke, Kathrin Fischer

The system optimal dynamic traffic assignment (SODTA) is a well-known problem for evacuation planning. While the SODTA provides an easy-to-use framework for traffic assignment, due to its linearity and natural integer variables, in its original form the SODTA also has several shortcomings with respect to its usefulness for realistic evacuation cases. These shortcomings include a) a lack of consideration of non-controllable evacuees and induced background traffic, b) different destination categories as well as evacuees with individual destination preferences, which lead to the well-known FIFO-problem, are not taken into account, c) a lack of consideration of the impact of individual evacuee behaviour.

In this presentation a comprehensive extension of the SODTA is introduced which considers a) the occurrence of non-controllable background traffic, b) the appearance of differing evacuee characteristics regarding destination preferences while prohibiting the occurrence of the well-known holding-back effect adjusted to multiple destinations and c) providing simulation results in order to assess the impacts of evacuee behaviour and the FIFO problem.

An illustrative case study as well as recommended algorithms for the parametrisation of background traffic and destination preferences are presented. The extension of the SODTA is evaluated regarding its usefulness and also its limitations for evacuation planning purposes. Further, the induced error resulting from the FIFO-problem is evaluated and discussed regarding its implications on the real life application of the newly developed model extensions.

4 - Separation of baggage increases the efficiency and experience of travelling.

Sicco Santema

Digitisation is one of the trends in mobility operations, creating possibilities for seamless travel from home to destination, across different modalities (PASSME, 2018). Digitisation is thus enabling changes in transport operations, away from the conventional infrastructure-based mobility system. In the PASSME (Personalised Airport Systems for Seamless Mobility and Experience) research, we looked at mobility from a traveller's perspective, a journey from home to destination. The objectives of the PASSME baggage operating research were: 1. To reduce the effect of the handling of baggage with respect to the travel time 2. To improve the traveller's experience through the ease of use and reduction of hassle. For traveller's experience we took the proxy 'stress' to measure the effect of baggage operations on the experience.

As research method, we used a co-design perspective on the creation of baggage models. Participants in the co-design sessions were representatives of stakeholders in a traveller's journey. Measurement of travel time was based on secondary data, enriched through own validation in airport operations. Measurement of stress and stress reduction was done through interviews in airport operations, validated through traveller's surveys.

From the research we learned that home to destination baggage transport (separated from the traveller's journey) saves the traveller 30 minutes of unwanted waiting time, on a one way trip. The surveys amongst travellers confirmed the positive effect of reducing stress points on the increase of the experience. All results have been in-depth evaluated with the stakeholders. The evaluation confirmed the outcome of our research, a reduced travel time and an increased experience.

■ TC-13

Thursday, 12:45-14:15 - 20.30 SR -1.025

Financial Management I

Stream: Finance
Invited session
Chair: *Merlin Bartel*

1 - Interpretable Machine Learning and economic data: Volatility spillover along the supply chains

Theo Berger

We introduce a financial network approach to quantify the impact of counterparty risk on firms' daily market risk, measured via conditional volatility.

We compare competing econometric and machine learning approaches and assess the economic interpretability of the applied machine learning algorithms.

We find that XGBoost in combination with SHAP values describe a sensible choice for large economic data sets which are described by a panel structure.

Also, suppliers are exposed to additional fundamental risk that is not captured by the suppliers' market beta, which gets transferred along the supply chains. The identified risk spillover impact both dimension and quality of the suppliers' market risk assessment: If customers experience large losses, suppliers' variance forecasts increase by (up to) 1% and the probability of suppliers' extreme losses doubles the next day.

2 - Investment Alternatives Selection to Maximize Low Income Investors Returns

Annegret Lewak

We observe strong growth in the renewable energy markets. So far most of the in-vestor base are institutional investors. Therefor also profits resulting from these projects are biased towards high disposable income segments of the population. In this talk we present a model that enables a shift of the bias towards low disposable income investor segments. Entrepreneurs want to act according to corporate social responsibility but not give up on their margins. Developing a model that supports both aims is the target of our research. By means of choosing optimal projects that support maximization of the returns of low disposable income investor segments an entrepreneur can build a win - win situation. The entrepreneur offers a decision-making parameter named "shared interest" in addition to the information about other project parameters. All investors have the choice to which extend they want to contribute to a fund (POT) for re - allocation towards low income investor segments. All income segments are weighted according to the segment size and the level of disposable income. Low disposable income segments will receive more out of the POT than high disposable income segments. This way we leverage the potential of low disposable income investor segments for renewable energies and maximize the returns towards these investor segments.

3 - Cost of Capital for ESG and Non-ESG Investments: Regression versus Theory-based Approaches

Ahmed Badreldin, Bernhard Nietert

Cost of capital is the most important aspect for investors when deciding to invest in ESG assets. Against this background there is a puzzle in the ESG literature. When formulating hypotheses or in-terpreting empirical findings, empirical ESG papers use one part of theoretical ESG papers, namely their economic interpretations regarding differences in cost of capital between ESG and non-ESG assets. Yet, to derive cost of capital, empirical ESG papers do not use the other part of theoretical ESG papers, namely their valuation formulas that determine the cost of capital for ESG and non-ESG assets. Instead, empirical ESG papers rely on multi-factor regressions to estimate cost of capital. Our paper brings, first, theory-based ESG pricing formulas in an empirically implementable form and shows, second, that the cost of capital estimates between regressions-(literature) and theory-based (our paper) cost of capital are significantly different, both statistically and economically. In this connection neither the sign nor the size of cost of capital differences can be forecasted. This result has two practical implications. First, using regressions, one can never be sure whether the theory-based cost of capital is over- or underestimated. Therefore, theory-based cost of capital should always be used even though they are way more tedious to empirically implement. Second, if cost of capital serves as an input for further empirical research, theory-based cost of capital should be applied since regression-based cost of capital might massively bias results.

4 - Diversifying Estimation Errors with Unsupervised Machine Learning

Merlin Bartel

Regarding the disastrous impact of estimation errors on portfolio optimization, this paper investigates the trade-off between optimization and estimation errors using unsupervised machine learning. Our model uses unsupervised machine learning to reduce estimation errors by clustering stocks into equally weighted portfolios which in turn are plugged into the classical minimum variance optimization. In contrast to previously documented results, the clustered optimization beats the equally weighted portfolio considerably in all setups. Varying the number of clusters from one (the equally weighted portfolio) to N (the minimum variance portfolio) we find the optimal number of clusters to be approximately N/4.

■ TC-14

Thursday, 12:45-14:15 - 10.50 Raum 702

Robust and Bilevel Optimization II

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Marc Pfetsch*

1 - Extensions of the Min-Max Regret Criterion for Combinatorial Optimization

Marc Goerigk, Michael Hartisch, Werner Baak

For decision making under uncertainty, min-max regret has been established as a popular methodology to find robust solutions. In this setting, we compare the performance of our solution against the best possible performance had we known the true scenario in advance. We introduce two generalizations of this setting. In the first approach, we compare against solutions that are also affected by uncertainty, which we call balanced regret. Using budgeted uncertainty sets, this allows for a wider range of possible alternatives the decision maker may choose from. We analyze this approach for general combinatorial problems and a type of selection problem. In computational experiments using random and real-world data, we show that balanced regret solutions provide a useful trade-off for the performance in classic performance measures. In the second approach, we move away from the notion that only the maximum regret is considered. Instead, we apply the ordered weighted averaging (OWA) criterion on the regret values to find a more general approach to map the decision maker's preference. We show that it is possible to derive approximation algorithms for this setting.

2 - Improved Algorithms for Robust Combinatorial Optimization

Mohammad Khosravi, Marc Goerigk

Having generated hard instances for robust combinatorial optimization, we use insights on properties of hard instances to introduce two classes of solution algorithms for robust combinatorial optimization that consider different ways of approaching these problems. These classes of solution algorithms consist of heuristics, approximation and exact solution algorithms.

For the first class, we consider robust optimization problems under discrete uncertainty sets. The main idea is to use an optimization-based data aggregation to construct a new uncertainty set which best represents the original set and also simplifies the problem. We consider different combinations of implementing clustering and aggregation phases including separately, simultaneously and iteratively. In addition, different methods of executing the clustering and aggregation steps are shown and their approximation guarantee discussed.

In the second class, we additionally include consideration of budgeted uncertainty sets. We establish algorithms based on a popular solution method that iteratively generates scenario constraints and variables. New techniques of stabilization are defined to improve the method by using less iterations or shorter solution time.

3 - Interdicting dense clusters in complex networks

Foad Mahdavi Pajouh, Haonan Zhong, Sergiy Butenko, Oleg Prokopyev

Assuming there is a cost associated with blocking vertices or edges, the objective of the interdiction problem is mostly to block a minimum-cost collection of vertices or edges to bound some critical structural property in the network.This paper introduces and investigates the problem of interdicting important dense clusters modeled as heavy-weighted quasi-cliques in a given network. We address the computational complexity of this problem, and formulate it as a linear 0-1 program. We develop a lazy-fashioned branch-and-cut algorithm and the first combinatorial branch-and-bound algorithm for this problem. The computational performance of these exact algorithms is then studied on a test bed of randomly-generated and real-life networks.

4 - A novel Reformulation Technique for a Large Class of Bi-Level Network Design Problems

Vladimir Stadnichuk, Maximilian Schiffer, Grit Walther

In the pursuit of sustainable and cost-efficient mobility, multimodal trips are gaining importance in today's transport systems. With the rising number of multimodal traveling options, both public and private transport companies face difficulties designing or extending modern transportation networks. From an optimization perspective, the underlying planning problem can be modeled as a bi-level optimization problem. Herein, the upper level constructs the multimodal network that maximizes revenue while taking budget constraints into account. The lower level represents route choices of users, who maximize their own objective, e.g., most comfortable or cost-efficient travel. The current state of the art for solving such problems focuses on applying the Karush-Kuhn-Tucker (KKT) conditions to the bi-level problem to obtain a single-level problem (SLP), solvable by of-the-shelf software. However, this state of the art suffers from a large number of complementary constraints, often leading to intractability for problem instances of realistic size. Against this background, we present a novel reformulation technique to derive an SLP. Under the mild assumption that the upper level is a binary problem, we are able to design an original linear program formulation of the lower level. This allows to use the strong duality theorem instead of KKT conditions, resulting in a leaner problem formulation. To further improve computational performance, we design new classes of valid inequalities, which are separable in polynomial time. Computational tests on several instances demonstrate that our approach outperforms the state-of-the-art KKT reformulation by orders of magnitude.

■ TC-15

Thursday, 12:45-14:15 - 10.50 HS 101

Learning and Discrete Optimization

Stream: Discrete and Combinatorial Optimization
Invited session

Chair: *Stefan Ruzika*

1 - An ML-based algorithm selection method to solve the min cost flow problem

Fabian von der Warth, Anna Meyer, Luca Schäfer, Philipp Herrmann, Stefan Ruzika

The minimum-cost flow problem is a classical problem in operations research and highly relevant in practice. A variety of solution algorithms exists for this problem, however, none of them outperforms the other solvers on all instances. Thus, the question arises whether it is possible to select the best algorithm given some instance of the minimum-cost flow problem. To this end, we train several machine learning classifiers to predict which solver is the fastest on a given instance. We accomplish this task by creating a representative data set of more than 80,000 instances and characterizing each of them by a vector of features. To achieve better performance, we optimize the hyperparameters of the classifiers. Finally, we evaluate the accuracy and a time-based metric. We identify the Random Forest classifier as a significant improvement over always choosing the algorithm with the best performance for a majority of problem instances.

2 - Machine learning supported prediction of dual variables for the cutting stock problem with an application in stabilized column generation

Sebastian Kraul, Markus Seizinger, Jens Brunner

This talk discusses a prediction model of the optimal dual variables for the (relaxed) cutting stock problem. For this purpose, we first analyze the influence of different attributes on the optimal dual variables within an instance for the cutting stock problem. We apply and compare our predictions in a stabilization technique for column generation. In most studies, the parameters for stabilized column generation are determined by numerical tests, i.e., the same problem is solved several times with different settings. We develop two learning algorithms that predict the best algorithm configuration based on the predicted optimal dual variables and thus omit the numerical study. Our extensive computational study shows the tradeoff between the learning algorithms using full and sparse instance information. We show that both algorithms can efficiently predict the optimal dual variables and dominate the common update mechanism in a generic stabilized column generation approach. While the learning algorithm with full instance information is applicable when one has to solve the problem mainly for a fixed set of items, the algorithm with sparse instance information is applicable when there is more variability in the number of items between the different instances.

3 - Using MILPs for generating robust adversarial examples

Rónán Rian Carl Richter, Jörg Rambau

The widespread use of Deep Neural Networks (DNNs) in various fields, including applications with increasingly higher security requirements, has made strategies to attack DNNs a relevant field of interest. One way to lead a DNN into wrong classifications are adversarial examples, i.e., small perturbations of inputs that result in false outputs. Different approaches for generating adversarial examples have been described in literature. However, adversarial examples may be heavily dependent on the given DNN, such that minor modifications of the DNN may rule out some of them. In the presented work, our goal is to find more robust adversarial examples for DNNs consisting of multiple layers of rectified linear units by building upon a MILP model proposed by Fischetti and Jo (2018). By incorporating perturbations of the weights and the biases of the rectified linear units, the resulting adversarial examples are more resistant to changes of the attacked DNN, e.g., by further training. We present examples for DNNs that are trained for MNIST data and compare our method with other approaches for generating robust adversarial examples, that are described in literature.

4 - Modeling and Exact Solution of Picker Routing and Order Batching Problems

Stefan Irnich, Katrin Heßler

We present a new modeling and solution approach for two-level problems in warehousing where one level concerns picking operations in a manual picker-to-parts warehouse. In particular, we consider the single picker routing problem with scattered storage (SPRP-SS) and the joint order batching and picker routing problem (JOBPRP). The SPRP-SS assumes that an article is, in general, stored at more than one pick position. The task is then the simultaneous selection of pick positions for requested articles and the determination of a minimum-length picker tour collecting the articles. In the JOBPRP, a set of orders is given, each with one or several order lines requesting a number of articles. The problem is here to group the given orders into capacity-feasible batches so that the total length of the picker tours collecting the respective articles is minimized. It is a classical result of Ratliff and Rosenthal that, for given pick positions, an optimal picker tour is a shortest path in the state space of a dynamic program with a linear number of states and transitions. We extend the state space of Ratliff and Rosenthal so that every feasible picker tour is still a path. Furthermore, the additional requirement to make consistent selections and grouping decisions can be modeled as additional constraints in shortest-path problems. We propose to solve these problems with a MIP solver. We

will explain why this approach is not only convenient and elegant but also generic: it covers optimal solutions to integrated problems that use heuristic routing policies for the picker tours, consider different warehouse layouts, and incorporate further extensions. Computational experiments with a direct MIP solver-based approach for the SPRP-SS and a branch-price-and-cut algorithm for the JOBPRP

■ TC-16

Thursday, 12:45-14:15 - 20.30 SR -1.012

Optimization under Uncertainty

Stream: Continuous and Global Optimization
Invited session
Chair: *Marcel Sinske*

1 - Data-driven Prediction of Relevant Scenarios for Robust Optimization

Jannis Kurtz

In this work we study robust one- and two-stage problems with discrete uncertainty sets which are known to be hard to solve even if the underlying deterministic problem is easy. Popular solution methods iteratively generate scenario constraints and possibly second-stage variables. This way, by solving a sequence of smaller problems, it is often possible to avoid the complexity of considering all scenarios simultaneously. A key ingredient for the performance of the iterative methods is a good selection of start scenarios. In this talk we propose a data-driven heuristic to seed the iterative solution method with a set of starting scenarios that provide a strong lower bound early in the process, and result in considerably smaller overall solution times compared to other benchmark methods. Our heuristic learns the relevance of a scenario by extracting information from training data based on a combined similarity measure between robust problem instances and single scenarios. Our experiments show that predicting even a small number of good start scenarios by our method can considerably reduce the computation time of the iterative methods.

2 - Global optimization for the multilevel European gas market system with nonlinear flow models on trees

Johannes Thürauf, Lars Schewe, Martin Schmidt

The European gas market is implemented as an entry-exit system, which aims to decouple transport and trading of gas. It has been modeled in the literature as a multilevel problem, which contains a nonlinear flow model of gas physics. Besides the multilevel structure and the nonlinear flow model, the computation of so-called technical capacities is another major challenge. These lead to nonlinear adjustable robust constraints that are computationally intractable in general. We provide techniques to equivalently reformulate these nonlinear adjustable constraints as finitely many convex constraints including integer variables in the case that the underlying network is tree-shaped. We further derive additional combinatorial constraints that significantly speed up the solution process. Using our results, we can recast the multilevel model as a single-level nonconvex mixed-integer nonlinear problem, which we then solve on a real-world network, namely the Greek gas network, to global optimality. Overall, this is the first time that the considered multilevel entry-exit system can be solved for a real-world sized network and a nonlinear flow model.

3 - Bayesian Optimisation for Ephemeral Resource Constraints

Stefan Pricopie, Richard Allmendinger, Manuel López-Ibáñez, Clyde Fare, Matt Benatan, Joshua Knowles

Ephemeral resource constraints (ERC) are a specific type of dynamic constraint that model the temporal availability of resources needed in the (physical) evaluation of solutions. Thus ERCs dictate which solutions are evaluable at a given moment rather than being feasible. Examples of ERCs include random machine breakdowns, periodic availability of staff/materials, limited storage space, shelf-life of resources, and temporary commitment to a certain instrument setting (as a consequence of previously made decisions).

Existing research in ERCs considers the augmentation of (customized) resource constraint-handling strategies on optimisation methods that are not well suited for expensive (black-box) problems, such as nature-inspired methods. Current strategies involve, for example, regenerating a non-evaluable solution until an evaluable one has been identified, or restricting optimization temporarily to be within the evaluable (as opposed to feasible) search space only.

The focus of this work is on tuning optimization methods designed for expensive problems to cope with ERCs. In particular, we consider the application of Bayesian Optimisation (BO), a sample-efficient approach for expensive black-box problems. We adapt BO to react to the dynamic search environment such that a (near-) optimal solution to a given problem is discovered as resource-efficiently as possible. A benchmark analysis is carried out on a series of test problems with ERCs, and algorithm performance is analysed. Finally, we discuss directions for future research.

■ TC-17

Thursday, 12:45-14:15 - 20.30 SR -1.011

Staff planning

Stream: Health Care Management
Invited session
Chair: *Katja Schimmelpfeng*

1 - Integrated Personnel and Task Planning

Gerriet Fuchs, Katja Schimmelpfeng

The shortage of qualified personnel is a well-known problem in the health care sector. As a consequence, two major challenges arise for hospitals. Qualified staff is becoming an increasingly scarce and expensive resource and staff satisfaction is an important objective in personnel planning. This means that both financial and fairness aspects have to be taken into account during the planning process. One tool to tackle both challenges is to introduce more flexibility into the personnel planning problem. We present a novel approach to a flexible integrated work schedule and task assignment problem. Our goal is to create flexible individual working plans based on given tasks. This individual approach allows us to consider, among other things, personnel preferences, work regulations and the fairness of the generated working plans. Task-based planning is a realistic problem setting in hospitals where flexibility could be a viable tool to address the above mentioned challenges. To explore the impact of flexibility, we introduce truly flexible and feasible work plans. These are created using a mixed-integer model that does not rely on arbitrarily defined time periods during a day. Therefore, the complexity of the planning problem is independent of the time granularity of the planning 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. In this way, we lay the groundwork for further research and identify steps that can be taken to improve personnel planning without compromising quality of care.

2 - A column generation approach for integrated surgery and staff scheduling in operating theatres on the operational level

Stefanie Ebel, Jens Brunner, Thomas Koperna

Two of the most important, costly and scarce resources in hospitals are physicians and operating rooms. Consequently, efficient and effective scheduling of both of these resources is one of the most relevant planning tasks within hospitals. As a result, efficient scheduling directly affects operating costs as well as patient and staff satisfaction and thus the quality of care. The decisions on the operational planning level regard the sequencing of patients' treatment as well as the assignment of appropriate staff to surgeries. Additionally, there are several interdependencies between surgery schedules and physician rosters. Therefore, it is a meaningful approach to consider both planning problems within one integrated optimization problem. Accordingly, we provide MIP models for a column generation algorithm that combines both scheduling problems within one solution approach and creates schedules for surgeries as well as for operating room staff. We are testing our algorithm with both exemplary test data and real-world data taken from a maximum care provider hospital in the south of Germany and provide meaningful insights.

3 - An approach for automated vacation planning in hospitals under consideration of employee satisfaction

Markus Schüller, Jens Brunner

In recent years, health care staff are confronted with several new challenges such as an increasing number of treatments, elaborate patient documentation, new diseases, e.g., COVID-19, or regulations, e.g., creating duty rosters, assigning vacation, procuring medical goods etc. Increasingly, valuable time is spent on organizational tasks rather than on the patient's bedside. By the automation of organization-oriented tasks, the workload of medical staff could be significantly reduced allowing a focus on patient's health. Most researchers in the field of organizational task automation in health care consider automated duty scheduling and exclude vacation planning in their analyses. In this work, we provide a Mixed-Integer Programming (MIP) approach to automate the vacation planning process. Employee satisfaction is, in addition, ensured by distinguishing between priority and regular leave wishes. The model is tested with both exemplary test and real-world data of the University Hospital of Ulm, Germany.

4 - Minimizing Employee Contacts in Rosters during Pandemic Times

Bastian Amberg, David Sayah, Boris Amberg

In this work, we consider rostering of employees with shift duties, e.g., nursing staff, in pandemic times. We extend the underlying duty rostering problem to include the minimization of potential contacts among staff members when assigning employees to shifts. This is intended to reduce avoidable contacts among employees over the planning period to reduce the risk of infection and employee absences. The latter can arise in particular from contact with infectious colleagues and the resulting quarantine obligation. We present a compact formulation that minimizes potential employee contacts in the rosters by allowing groups of employees to work together in the same constellation for as long as possible. The formulation considers the usual rostering objectives, e.g., balanced working hours, fulfillment of shift preferences, and day-off preferences. In contrast to planning with separate teams who work together over the entire planning period, our model enables more flexible use of the available staff depending on the chosen objectives. We enhance a standard MIP formulation that uses time-indexed decision variables for assigning employees to shifts with a graph-based model. The novel model allows us to track contacts that occur within shifts and temporary teams in rosters on a per-employee basis. Of course, in practice, there can still be illnesses among employees and absences due to quarantine obligations. Therefore, we suggest another extension of the rostering problem that allows for the anticipation of quarantine-induced staff shortages. We show that our model lays the foundation to handle these based on two cases where employee absence can be triggered by the accumulation of either working time in a potentially infectious environment or potentially infectious contacts.

■ TC-18

Thursday, 12:45-14:15 - 20.30 SR -1.013

Simulation for Industrial Assessment

Stream: Simulation
Invited session

Chair: *Max Krueger*
Chair: *Maximilian Moll*

1 - Simulative Assessment of Patrol Car Allocation and Response Time

Tobias Cors

In the planning of police forces an adequate allocation of resources to dis-tricts is crucial for providing an effective and robust service and for main-taining acceptable emergency response times. Due to the high operational heterogeneity and variability, determining reliable profiles for resource uti-lization and establishing their relationship to response times is a challeng-ing task in and of itself that requires an adequate consideration of several sources of stochastic influence. Prior approaches from police practice main-ly consider static ratios (e.g., resources per number of inhabitants or calls for service) in order to estimate capacity demand. Based on an extensive da-taset comprising more than two million items, we estimate stochastic process models for all relevant police operations in a major metropolitan area and use a discrete-event simulation to analyze capacity utilization and re-sponse times of a given fleet of police vehicles. The simulation model pre-dicts the spatial and temporal occurrence of police operations and dispatch-es available vehicles from different districts, in order to model resource sharing in emergency response. The human dispatcher is mimicked by an observed set of static and workload-based rules. The vehicle allocation is then optimized via a rule-based heuristic, observing shift patterns and local demand structure, until response time expectations are met. This provides key insights into the required capacity over time and constitutes a crucial first step for an adequate capacity planning.

2 - Simulating the impact of occasional drivers on food distribution in alternative food networks

Florian Cramer, Christian Fikar

This work considers the use of occasional drivers (ODs) to perform physical distribution for perishable food in short food supply chains (SFSCs). Any breach in the cold chain can have detrimental effects on the items' value as well as on food quality and safety. The use of everyday people, ODs, whose vehicles usually do not offer cold storage options, thus presents a potential economic and environmental threat. This work develops a decision support system (DSS) based on agent-based and discrete event simulation modelling to explore the use of ODs for last-mile physical distribution of perishable food items sold by local farmers. The DSS enables one to study the potential increase in farmer's market reach and related trade-offs such as food quality loss and an increase in kilometres travelled. Results show that the effects depend on the population setting (urban versus rural). The use of ODs in a rural setting leads to a bigger increase in farmer's market reach. The impact on kilometres travelled depends on when and where the ODs start participating. When only considering shoppers the travel distance increases, whereas when considering shoppers and non-shoppers the distance can be decreased. In general, the use of ODs for last-mile food distribution can hold a significant potential to increase smallholder farmers' market reach within alternative food networks.

3 - Simulation Model to Assess the Impact of Demand Disruptions in Short Food Supply Chains

Suad Saliju, Christian Fikar

Research in short food supply chains has increased notably in recent years, mainly due to their likely role of achieving a more sustainable and resilient food system. Meanwhile, an ever-increasing number of disruptions are severely affecting the functioning of food supply chains. Considering the perishable nature of various food produces, it is of great importance to act rapidly in case of a sudden disruption to minimize any economic impact and food losses. To this end, a hybrid simulation model is developed, which enables one a cost-effective approach to address resilience in the context of short food supply chains. Resilience is addressed in the model by evaluating the degree of using different distribution channels based on post-harvest costs and food losses estimated by integrating food quality functions. The developed simulation model is demonstrated on a regional asparagus supply chain in Franconia, Germany. Results show the relevance of enabling alternative distribution channels to facilitate both resilience and reduction in food losses but also that the timing of the disruption is of importance.

4 - Comparison of adoption rates of hydrogen, hydrogen-electric and SAF in the future air transport system with a system dynamics model

Chetan Talwar, Imke Joormann, Thomas Spengler

Aviation has been criticized for its negative climate impact in the past few years. This is due to the emission of harmful greenhouse gasses (GHGs) such as CO2, NOx and water vapour that can cause the formation of climate harming ozone and contrails. It is estimated that aviation may be producing as much as 24 % of global CO2 emissions by 2050, compared to roughly 3 % today. In recent years, many different technologies have surfaced that have the potential to replace the existing conventional jet fuel technology. On one hand, H2 powered aviation just recently regained high attention from the industry, e.g., Airbus launched the ZERO-E program where they pledged to develop the world's first zero-emission commercial aircraft by 2035. On the other hand, sustainable alternative fuels (SAF) or biofuels have been identified as an alternative option. It has been found that certain SAF production routes can provide a 73 - 84 % of life cycle assessment based GHG reduction compared to fossil fuel-based kerosene. Given the different promising future technologies, it is difficult to predict their role in transition pathways that will lead the air transport system towards a more sustainable future. We develop a global scale system dynamics air transport system simulation model and incorporate components like the new potential technologies, production side emissions of new fuels (i.e., SAF and hydrogen), air travel demand, airline industry and aircraft manufacturers. We also include the long, medium and short haul segments of flights. Using this model, we analyze the adoption trends of new technologies and fuels by assessing the amount of fleet operated with them and its effect on emission reduction within each flight segment.

■ TC-19

Thursday, 12:45-14:15 - 20.30 SR 0.019

Optimal Planning and Operation of Technical Systems

Stream: OR in Engineering
Invited session
Chair: *Johannes Schmidt*

1 - Temperature-based trajectory planning for surfaces in Wire-Arc Additive Manufacturing

Johannes Schmidt, Armin Fügenschuh, Johannes Buhl

In the process of Wire-Arc Additive Manufacturing (WAAM), the desired workpiece is split up into slices and built up layer-by-layer. The welding head can move freely over the clamped substrate plate to deposit droplets of metal wire, molten by an electrical arc or a laser. Also, transfer moves without welding are possible. The main issue about this manufacturing technique is the temperature distribution within the work- piece since the large thermal gradients caused by the welding process can cause thermal stress, leading to strain or even cracks. Especially for filled surface structures consisting of many weld beads, this must be taken into account. Thus, careful planning of the welding trajectory is essential for high-quality workpieces. We consider the trajectory planning problem of finding an optimal welding trajectory for a given two-dimensional layer. It is formulated as a mixed-integer linear problem (MILP) searching the welding path with the most homogeneous temperature distribution during the manufacturing process. The heat conduction, the weld source, and the heat exchange with the environment are incorporated into the model using a two-dimensional finite element method. All MILP instances are solved to global optimality using a linear programming based branch-and-cut approach, offered by standard solvers such as Cplex. For several standard surface shapes, the computed optimal trajectory is compared to commonly used strategies like raster, zigzag or spiral paths.

2 - Operational optimization of Water Distribution Networks based on Mathematical Programs with Equilibrium Constraints

Felix Lenders, Eike Fokken, Marco Lauricella, Matthias Biskoping, Matthias Schlöder

A significant portion of the operating costs associated with drinking water distribution networks is related to energy usage, and up to 70% of that energy is employed to drive pumps. Energy and cost optimization of water distribution networks represents an important practical problem, both in terms of operating cost and energy consumption reduction. In particular, the optimization of pump operations scheduling is a critical tool that helps reducing the total cost of energy for distribution network operators, the total energy consumption of pumps and associated greenhouse gas emissions.

Numerical optimization of water distribution networks operation is a difficult problem to solve, since it features non-linear and non-convex hydraulic dynamics of water networks and discrete decision variables, corresponding to pump and valve switching. Standard formulations of hydraulic models for water distribution networks such as the industrial quasi standard implemented in the EPANET package include discontinuities and are thus not amenable to standard nonlinear programming techniques.

In this work, we present the results of the application of nonlinear programming techniques to the problem of pump operations scheduling for medium-sized real-world water distribution networks. We employ an equilibrium/complementarity constraint based description to model switching behavior and compare different nonlinear formulations of the complementarity . We present industrial case studies of energy cost optimization for the operation of several water networks and highlight the practical challenges on scaling towards real-world water distribution networks.

3 - Development of solution algorithm for fully LR-type interval-valued intuitionistic fuzzy linear programming problems using lexicographic-ranking method

Manisha Malik, S. K. Gupta

Linear programming problems (LPP) are extensively used to solve many practical problems. However, due to the presence of various inevitable factors like recording errors, financial up/down in the market, etc., the construction of LPPs in an imprecise environment is of utmost importance. The concept of fuzzy numbers (FN) fits better to handle any ambiguity in the input data of a problem. Initially, ranking functions have been used to convert fuzzy LPPs into crisp optimization problems. Thereafter, to overcome the limitations of ranking functions, the idea of lexicographic ranking criteria came which uses multiple parameters at a time associated with an FN leading to a more effective and powerful ordering technique. The fuzzy sets were later on extended to the interval-valued intuitionistic fuzzy (IVIF) sets which use intervals to define the membership and non-membership degrees for each element of the set. Additionally, to represent any type of variation in the input data, the LR-type FNs play a crucial role in optimization theory. Thus, in the present study, we have first introduced the concept of LR-type IVIF numbers (IVIFN) and developed the basic arithmetic operations on unrestricted LR-type IVIFNs. The total order properties of lexicographic ranking criteria have been utilized for ordering the LR-type IVIFNs. Further, a novel algorithm is proposed to obtain the unique optimal solution of an LPP having both equality and inequality type constraints with all the parameters and decision variables taken as LR-type IVIFNs. The proposed technique has not only introduced a new idea but also generalized various well-known related works existing in the literature. Finally, a practical application in production planning is solved and examined using the proposed approach.

4 - Learning strategies for outsourcing problems with asymmetric information and uncertain execution

Alexander Herbst

Nowadays the requirements on effectiveness and efficiency are rapidly growing for many companies. To avoid the irritation of longtime customers or even penalty fees, one main task in this context is the on-time provisioning of products and services. Simultaneously, technologies like digital signatures or smart contracts lead to novel possibilities for immediate and mandatory agreements between all kinds of market participants - meaning not only humans or companies but even different entities of artificial intelligence. In this contribution, we consider an outsourcing problem based on a specific principal-agent relationship with hidden characteristics. Under the assumption that the principal knows the probability distribution on the agent's discrete type space, a standard solution technique for the resulting contracting problem is stochastic optimization on the set of incentive compatible menus of contracts from which the agent can choose a single contract according to the take-it-or-leave-it principle, respectively. Admittedly, this approach neglects any sort of uncertainties in the post-contract phase which is not realistic in many practical environments like production and logistics. To address this issue, we present a novel and holistic problem formulation that links the contracting phase to an uncertain execution phase in a logistical context containing the possibility of renegotiating contracts as a reaction to environmental changes. Since the resulting problem has the character of a multi-round game, we apply well-known concepts from the trendy AI-area of Deep Reinforcement Learning to exploit clever contracting strategies for the principal. Finally, we evaluate our approach inside a computational study.

■ TC-20

Thursday, 12:45-14:15 - 20.30 SR 0.016

Revenue Management and Choice Behavior

Stream: Pricing and Revenue Management
Invited session
Chair: *Catherine Cleophas*

1 - Optimal Pricing in face of Endogenous Network Effects and Customer Heterogeneity

Oliver Vetter, Cornelia Schoen

We consider a profit maximization problem to determine the optimal prices of multiple products in face of network effects and customer heterogeneity. The demand for a product is assumed to be dependent on the product quality, the price, and an endogenous network effect. The network effect describes a behavior where customers are more likely to purchase a product if the product already has a larger market share. It is assumed that the population is split into multiple segments where the partial utilities of product attribute levels are heterogeneous for customers between different segments and homogenous in the same segment. To estimate demand the well-known Mixed Multinominal Logit (MMNL) model with discrete mixture distribution is applied. Former scholars have only considered simpler models so far, such as the single-segment multi-product case by Du, Cooper,

and Wang (2016) and the multi-segment single-product case by Nosrat, Cooper, and Wang (2021). Our work extends these approaches to the more complex multi-segment multi-product setting and differs in the applied solution method. We develop a linear relaxation of the optimization problem to solve the problem approximately. In addition, properties under which the exact solution can be found are derived. We compare our new approach with different heuristics and a commercial solver in an extensive numerical study for both discrete and continuous prices and show that its performance is promising in terms of solution time and solution quality.

2 - Markov Chain Choice on a Real Interval

Jonas Rauch

We present a parametric, continuous version of the Markov Chain Choice model for the case where products are defined by a single real-valued attribute, such as the departure time of a flight in a schedule.

The model is derived as the continuous limit of the discrete Markov Chain Choice model on a one-dimensional product space. Customer choice behavior is represented by a continuous-time Markov process, consisting of two interdependent stochastic processes: A diffusion process that models the customer's transition through the space of candidate products, and a jump process that represents a transition to the no-purchase option. We give explicit analytic expressions for the choice probabilities assuming piece-wise constant model parameters. Furthermore we show that our model yields instances of the discrete Markov Chain Choice model, which allows us to directly apply many known extensions of the discrete MCC model.

The continuous MCC model combines the advantages of different classes of customer choice models: Like the discrete MCC model, it offers realistic recapture behavior while still being numerically tractable. Due to its parametric nature, it allows to extrapolate and predict choice probabilities for previously unobserved products. Lastly, all model parameters have an intuitive interpretation, which allows experts to validate the model and gain managerial insights. These properties make the model particularly attractive for practical applications in airline revenue management or network planning, or in similar contexts in other industries where schedules change frequently.

3 - Estimation of a Consider-Then-Choose Customer Choice Model for Tractable Assortment Optimization

Jonas Schwamberger, Moritz Fleischmann, Arne Strauss

In attended home delivery services, the time slot offering problem is of high importance, as it significantly impacts the retailer's efficiency in providing this service. Customer choice behavior is a crucial factor to be considered in this planning problem. To facilitate this task, customer choice models have been developed that reflect the customer decision-making process. A particularly realistic choice model is the consider-then-choose model. This non-parametric customer choice model consists of two steps: in a first step, all eligible time slots are identified and in a second step, the considered time slots are ranked and the highest-ranked time slot is chosen. In this study, we use the consider-then-choose model to solve the time slot assortment problem. We propose an approach to estimate this choice model from historical transaction data and incorporate a structure that can be exploited in the online time slot offering decision. We evaluate our estimation and optimization approach in a realistic numerical study.

4 - Exploring Behavioral Aspects of Demand Management

Catherine Cleophas

In practice, demand management systems combine forecasting and optimization algorithms with human decision-making. However, only a few existing contributions consider the behavioral aspects of demand management. In an extended experimental design and a corresponding laboratory study, we examine the impact of non-stationary demand and two dynamic decision tasks. In addition, we explore strategies and biases by comparing subjects' decisions to systematic heuristics. Our results highlight that participants struggle to accommodate a non-stationary customer value. In that, they exhibit a combination of optimism and loss aversion biases. We further find that subjects anchor their decisions on simplified components of the announced forecast. Finally, we highlight implications and further research opportunities to behaviorally inform the design of symbiotic analytics systems from these results.

■ TC-21

Thursday, 12:45-14:15 - 30.96 Seminarraum 1. OG (R104)

Project Planning and Assembly Lines

Stream: Project Management and Scheduling
Invited session
Chair: *Julia Rieck*

1 - Project Planning for Engineering Automotive Production Systems

Maximilian Kolter, Martin Grunow, Rainer Kolisch, Thomas Staeblein

In the automotive industry, ever shorter product life cycles and growing product portfolios have led to a high frequency of new product launches. The production systems for these products are usually very complex and product specific. Therefore, each new product introduction is associated with a project to engineer and implement its production system. For undertaking these projects, car manufacturers deploy inhouse manufacturing engineers and use outsourcing services from engineering services providers. Planning these projects requires the car manufacturer to decide on how many inhouse engineers to deploy, how to assign these engineers to activities, and which activities to outsource to which service providers. In practice, this planning problem is solved manually and is not optimized. Therefore, we present a multi-objective mixed integer programming model based on the resource-constraint multi-project scheduling problem to solve the planning problem at hand. We consider two lexicographic objectives. The first objective maximizes the utilization of inhouse engineers, which is equivalent to minimize outsourcing. The second objective minimizes jumps in the resource profiles for the service providers to generate attractive outsourcing bundles. Using realistic data from a major European car manufacturer, we conduct a computational study to obtain managerial insights into optimal project schedules, workforce compositions, and outsourcing strategies.

2 - Continuous-Time Formulations for Multi-Mode Project Scheduling

David Sayah

In this talk we review state-of-the-art continuous-time approaches to formulating the multi-mode resource-constrained project scheduling problem as a mixed-integer program. We first present a start-end-event-based formulation which corrects a prevailing flaw of existing models. Specifically, our model ensures consistency across the operational modes that must be chosen for each activity. We also propose an alternative model that relies on the known concept of on-off-events. Second, we improve an existing network flow formulation. We enhance our models by adapting several techniques that have been used previously, e.g., in cases with only a single mode. A large set of benchmark instances from the literature provides the basis for an up-to-date and fair computational study with an out-of-the-box solver package. We compare our models against an existing assignment-based model. Our experiments assert confidently that network flow formulations prevail over all other tested models, whereas event-based models become less competitive than in single-mode settings.

3 - Solution Algorithms for Resource-Flexible Multi-Skill Project Scheduling Problems

Niels-Fabian Baur, Julia Rieck

In the context of project scheduling, activities between which precedence constraints exist, are to be scheduled over the time axis in such a way that, e.g., the project duration is minimized. It is often assumed that the activities have deterministic durations and resource requirements. In reality, however, project scheduling is subject to stochastic influences that must not be neglected. Here, the duration of activities is often unknown and resources (i.e., production employees or disaster response workers) have different skills that must be taken into account. In addition, the number of resources or workers used to process an activity can be varied. This results in flexible resource profiles. The duration of an activity thus depends on the number of workers per period as well as the corresponding skills, and an activity can be considered as completed when the estimated total workload is reached. Furthermore, we allow interruptions for the activities and consider partially renewable resources. The problem can therefore be referred to as a resource-flexible multi-skill project scheduling problem. We present a mathematical model for the problem based on scenarios, where a scenario is generated by picking triangularly distributed random numbers for the stochastic total workloads. A project schedule is sought that

minimizes the expected project duration across all scenarios. For this purpose, a hill-climbing method and a scatter search are introduced to determine a best possible solution. Since these methods require a high computational effort, a Q-learning approach is additionally presented and finally compared with the scenario-based solution methods.

■ TC-22

Thursday, 12:45-14:15 - 20.30 SR -1.008 (UG)

Energy Applications

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *Jake Atkinson*

1 - Planning of rotor blade maintenance processes on onshore wind turbines

Martin Klingebiel, Carolin Kellenbrink

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 present both a model and a heuristic solution approach for the routing and scheduling of service teams to perform maintenance activities at different locations with minimum total costs. Using real-world data from an onshore wind turbine manufacturer we systematically generated instances and then conducted numerical studies to evaluate and compare the performance of our proposed model and heuristic.

2 - A Heuristic Solution Approach for Planning Inductive Charging Infrastructures on Airport Aprons

Niklas Pöch

Due to climate change, sustainability is playing an increasingly important role in the aviation sector. One measure to reduce emissions is the electrification of ground vehicles on the airport apron. Dynamic inductive charging, in which vehicles are charged wirelessly while driving, is particularly suitable for apron vehicles. Compared to conductive charging, this technology has the advantage of eliminating downtime for charging the vehicles. The design of such an infrastructure is challenging, as both technical and economic constraints need to be considered. We present a model to determine the design of the charging infrastructure while minimizing the investments. Solving the model with exact solvers like Gurobi for instances of real-world problem sizes requires extremely high computation times. For this reason, we present a heuristic solution approach for this problem.

3 - Optimal Agent Deployment and Energy Aware Data Routing in Heterogeneous IoT Networks for Remote Control of Agricultural Areas

Banu Kabakulak

In this study, we consider an internet of things (IoT) network which consists of various agents such as sensors, actuators, routers and gateways to remotely monitor agricultural lands. The network can continuously gather data from the land with sensors, send them to a cloud server via routers and gateways. The collected data can be real-time analyzed in the cloud database, which allows to instantly send commands to the actuators. As an example, the soil humidity sensor data can indicate dryness and the cloud algorithms decide to initiate the irrigation actuators in the network for watering.

In this work, we focus on the energy-efficient design and control of a heterogeneous IoT network through optimally (1) finding the agent locations for connected coverage of the target land, (2) determine the active/sleep schedules of the agents to prolong the network lifetime, (3) route the sensed data over minimum energy consuming paths to the gateways. The ultimate goal of the IoT network is to sense the target region as long as possible within the limited budget for the deployment of the agents and the limited battery energy of the sensor nodes. We process the problem on three stages, i.e., agent deployment, activity scheduling and data routing, and propose mathematical models for each stage. Afterwards, we introduce polynomial-time efficient heuristic methods since each stage is NP-hard. We tested the performance of our heuristic approaches via computational experiments. The results indicate that our approach can be implementable for real-time monitoring of large agricultural lands. Our heuristics can also be extended to other IoT networks such as smart factories which collect real-time data from the production stages, evaluate and take actions based on the algorithms.

4 - Inventing and Assessing Simple Heuristics for Bidding in Wholesale Electricity Markets

Jake Atkinson, Richard Allmendinger, Joshua Knowles

In areas of commerce, fast and frugal heuristics have a demonstrated history of forecasting as or more accurately than complex statistical strategies. Above all, heuristics offer computational economy over sophisticated methods that demand vast resources. Financial participation in the deregulated electricity market in the USA requires accurate forecasting and presents an opportunity for the implementation of heuristics by traders seeking to arbitrage.

Developmental research was undertaken to invent and assess simple heuristics for bidding in wholesale electricity markets. Heuristics were developed based on an evolution of existing strategies currently implemented in industry. Research was guided by industry partner Invenia Labs.

Assessed bidding strategies demanded accurate forecasting, contingent on high resource availability. Two heuristic price-adjustment bidding strategies were developed, providing modest returns relative to existing strategies, greater risk-aversion and reduced computational and time complexity. Forecasting was based on a year's worth of historical pricing data from the Pennsylvania, New Jersey, Maryland Independent System Operator.

Thursday, 14:30-15:30

■ TD-01

Thursday, 14:30-15:30 - 30.95 Audimax A & B

Plenary talk Pankratius

Stream: PC Stream
Plenary session
Chair: *Kai Furmans*
Chair: *Victor Pankratius*

1 - Sensing Applications as a Driver for Edge-AI Solutions
Victor Pankratius

New generations of sensors are increasingly equipped with microcontrollers and computing capabilities that enable local machine learning in millimeter-sized packages. This talk presents examples and use cases where sensing applications have become a major driver for artificial intelligence in ultra-low power contexts at the edge. Applications are shown for intelligent Micro-Electro-Mechanical Systems (MEMS) in motion learning in mobile & wearable devices, work ergonomics, sports analytics, as well as gas and environmental sensing. Supply chain optimizations will be able to leverage smart sensors equipped with enhanced inertial navigation where GPS is unavailable, thus enabling new capabilities in asset tracking for billions of assets. Looking at the software stack, this talk also addresses the importance of formalizing and including domain knowledge into machine learning as an additional lever for optimizations, such as shrinking memory footprints, making trade-offs in signal processing, and selecting algorithms. Learning from individual success stories, our insights help sketch a bigger picture for technology ecosystems and platforms that are beginning to take shape, and how various groups and communities can be engaged.

Thursday, 15:45-16:30

■ TE-01

Thursday, 15:45-16:30 - 30.95 Audimax A & B

Tutorial by Gurobi

Stream: PC Stream
Tutorial session
Chair: *Simon Bowly*

1 - Learn About Gurobi's Educational Resources & Play Our New Optimization Game
Simon Bowly, *Lindsay Montanari*

Gurobi is a company that has education at the core of what we do; because of this, we strive to find ways to give back to the optimization community that has helped shape us. Gurobi Optimization has developed and released open education tools to teach users why optimization is valuable, why it's difficult, and why solvers and other optimization algorithms are essential in finding the best solution for their problem solving.

Gurobi also makes its commercial solver available for free for academic use. In addition, we are developing and releasing tools to help with analysis of benchmark results in research. In this talk we'll introduce our log-parsing tool and show how it can be used for parameter tuning and performance analysis when developing mathematical programming models.

The Game: www.burritooptimizationgame.com

■ TE-05

Thursday, 15:45-16:30 - 11.10 Engelbert-Arnold-Hörsaal (EAS)

Interactive Tutorial by PTV

Stream: PC Stream
Tutorial session
Chair: *Lars Moritz*

1 - Urban logistics - fast track to mobile apps
Lars Moritz

We show in a step by step coding how mobile apps for optimizing urban logistics problems can be realized by using PTV Developer components.

Thursday, 16:30-17:15

■ TF-01

Thursday, 16:30-17:15 - 30.95 Audimax A & B

Workshop Wolfram Research/Mathematica

Stream: PC Stream
Workshop session
Chair: *Jon McLoone*

1 - Unified Computation in OR - More than just optimisation
Jon McLoone

Wolfram's vision of unified computation is a high-level programming language where any computation you might need is built in and designed to work together without the need of external library or programs. While this includes the full range of industrial scale optimization that would be in an OR tool, it extends to include Machine Learning, Time Series and Image Analysis.

In this talk using live demos we will show, how you can produce new insights and support research work flows from computation through to deployment. Furthermore, having unified design enables greater automation so OR Researchers can express problems at a higher level with less coding. The talk will be illustrated with examples from many domains, including manufacturing, transport and resource allocation, and will include computations using graph theory, linear and nonlinear optimization, and system modelling.

■ TF-04

Thursday, 16:30-17:15 - 10.11 Hertz-Hörsaal

Interactive Tutorial by IBM

Stream: PC Stream
Tutorial session
Chair: *Sebastian Fink*

1 - Prototyping and Deploying Optimization-based Applications
Sebastian Fink

Based on examples, I will present and walk through prototyping and deploying an optimization-based application in IBMs Decision Optimization Center framework (https://www.ibm.com/cloud/decision-optimization-center).

Thursday, 17:30-19:00

■ TG-01

Thursday, 17:30-19:00 - 30.95 Audimax A & B

GOR Annual Meeting

Stream: PC Stream
Invited session

Friday, 8:30-10:00

■ FA-04

Friday, 8:30-10:00 - 10.11 Hertz-Hörsaal

GOR Young Researchers Awards

Stream: PC Stream
Award Competition session
Chair: *Alexander Martin*

1 - Last-mile delivery concepts: a survey from an operational research perspective
Stefan Schwerdfeger, Nils Boysen, Stefan Fedtke

In the wake of e-commerce and its successful diffusion in most commercial activities, last-mile distribution causes more and more trouble in urban areas all around the globe. Growing parcel volumes to be delivered toward customer homes increase the number of delivery vans entering the city centers and thus add to congestion, pollution, and negative health impact. Therefore, it is anything but surprising that in recent years many novel delivery concepts on the last mile have been innovated. Among the most prominent are unmanned aerial vehicles (drones) and autonomous delivery robots taking over parcel delivery. This presentation surveys established and novel last-mile concepts and puts special emphasis on the decision problems to be solved when setting up and operating each concept. To do so, we systematically record the alternative delivery concepts in a compact notation scheme, discuss the most important decision problems, and survey existing research on operations research methods solving these problems.

2 - An ALNS algorithm for the static dial-a-ride problem with ride and waiting time minimization
Arne Schulz, Christian Pfeiffer

The paper investigates the static dial-a-ride problem with ride and waiting time minimization. This is a new problem setting of significant practical relevance because several ride-sharing providers launched in recent years in large European cities. In contrast to the standard dial-a-ride problem, these providers focus on the general public. Therefore, they are amongst others in competition with taxis and private cars, which makes a more customer-oriented objective necessary. We present an adaptive large neighbourhood search (ALNS) as well as a dynamic programming algorithm (DP), which are tested in comprehensive computational studies. Although the DP can only be used for a single tour and, due to the computational effort, as a restricted version or for small instances, the ALNS also works efficiently for larger instances. The results indicate that ride-sharing proposals may help to solve the trade-off between individual transport, profitability of the provider, and reduction of traffic and pollution.

3 - An SDP-Based Approach for Computing the Stability Number of a Graph
Elisabeth Gaar, Melanie Siebenhofer, Angelika Wiegele

Finding the stability number of a graph, i.e., the maximum number of vertices of which no two are adjacent, is a well known NP-hard combinatorial optimization problem. Since this problem has several applications in real life, there is need to find efficient algorithms to solve this problem. Recently, Gaar and Rendl enhanced semidefinite programming approaches to tighten the upper bound given by the Lovász theta function. This is done by carefully selecting some so-called exact subgraph constraints (ESC) and adding them to the semidefinite program of computing the Lovász theta function. First, we provide two new relaxations that allow to compute the bounds faster without substantial loss of the quality of the bounds. One of these two relaxations is based on including violated facets of the polytope representing the ESCs, the other one adds separating hyperplanes for that polytope. Furthermore, we implement a branch and bound (B&B) algorithm using these tightened relaxations in our bounding routine. We compare the efficiency of our B&B algorithm using the different upper bounds. It turns out that already the bounds of Gaar and Rendl drastically reduce the number of nodes to be explored in the B&B tree as compared to the Lovász theta bound. However, this comes with a high computational cost. Our new relaxations improve the run time of the overall B&B algorithm, while keeping the number of nodes in the B&B tree small.

■ FA-05

Friday, 8:30-10:00 - 11.10 Engelbert-Arnold-Hörsaal (EAS)

Design and Ramp-up of Manufacturing Systems

Stream: Supply Chain Management
Invited session
Chair: *Justus Arne Schwarz*

1 - Ramp-up with stochastic and non-stationary yield: Insights from a Newsvendor approach
Justus Arne Schwarz, Johannes Diefenbach, Fikri Karaesmen, Raik Stolletz

Our research is motivated by the planning problem of a global manufacturer of semiconductors. During the introduction of a new product or machine, the yield of a production process tends to start low and increases with the production quantity. This is known as the ramp-up phase. Due to long production lead times the company has to choose the production quantity during the ramp-up phase ex-ante. We formalize the company's problem as a Newsvendor problem with stochastic and non-stationary yield and deterministic demand. We derive analytical and numerical insights on the optimal ramp-up quantity and the expected profit. We prove that the expected profit is a discrete concave function of the production quantity for stationary yield and characterize the optimal production by a critical-fractile. However, this does not hold for the case of increasing yield. A numerical study shows that the optimal production quantity using the proposed model is close to the ex-post optimal production quantity from the data. Moreover, we show numerically that an increase in the yield learning curve can lead to a non-monotonic behavior of the optimal production.

2 - Validation of a meta-model approach for setting order release parameters in engineer-to-order systems
Jana Philips, Ralf Gössinger

In engineer-to-order systems, the additional uncertainties of specification time and capacity requirements are relevant for releasing orders. A MILP model for order release has been proposed, in which these stochastic variables are estimated using chance-constraints. This requires probability thresholds that need to be specified in advance as parameters. In order to obtain clues for favorable parameter settings, we propose a new data-driven multi-criteria approach that takes cost and robustness measures into account. The approach consists of four steps: (1) Data generation: A database of problem instances and related solutions is generated and aggregate performance values are calculated. (2) Meta-model estimation: The model considers the impact of both, planning situation and parameter values, on the aggregate performance. (3) Parameter recommendation: Favorable parameter values are derived by algebraically analyzing the meta-model. (4) Validation of recommendation quality: Model fit and predictive ability are verified by statistical means. The suitability of this approach is demonstrated by a comprehensive numerical study. Systematically generated problem instances are solved with regard to the cost objective. For each combination of planning situation and parameter values, the minimum cost levels and observed robustness values of the solutions are aggregated to normalized performance values. A second-order polynomial that accounts for two-factor interactions is used to estimate the meta-model. The ability of the approach to predict favorable parameter values is assessed by a Monte Carlo cross-validation.

3 - A novel decomposition-based method for solving general-product structure assemble-to-order systems
Mohsen Elhafsi, Jianxin Fang, Essia Hamouda

Assemble-to-order (ATO) strategies are common to many industries. Despite their popularity, ATO systems remain challenging to analyze. We consider a general-product structure ATO problem modeled as an infinite horizon Markov decision process. As the optimal policy of such a system is computationally intractable, we develop a heuristic policy that is based on a decomposition of the original system, into a series of two-component ATO subsystems. We show that our decomposition heuristic policy (DHP) possesses many properties similar to those encountered in special-product structure ATO systems. Extensive numerical experiments show that the DHP is very efficient. In particular, we show that the DHP requires less than 10^{-5} the time required to obtain the optimal policy, with an average percentage cost gap less than 4% for systems with up to 5 components and 6 products. We also show that the DHP outperforms the state aggregation heuristic of Nadar et al. (2018), in terms of cost and computational effort. We further develop an information relaxation-based lower bound on

the performance of the optimal policy. We show that such a bound is very efficient with an average percentage gap not exceeding 0.5% for systems with up to 5 components and 6 products. Using this lower bound, we further show that the average suboptimality gap of the DHP is within 9% for two special-product structure ATO systems, with up to 9 components and 10 products. Using a sophisticated computing platform, we believe the DHP can handle systems with a large number of components and products.

■ FA-06

Friday, 8:30-10:00 - 10.91 Redtenbacher-Hörsaal

Decision Analysis for Sustainability and Resilience

Stream: Decision Analysis and Support
Invited session
Chair: *Marcus Wiens*

1 - A Novel Framework to deal with Ambiguity in the Humanitarian Decision Making

Emilia Grass, Janosch Ortmann, Burcu Balcik, Walter Rei

One of the major challenges for humanitarian organizations when planning relief efforts is dealing with the inherent ambiguity and uncertainty in disaster situations. The available information that comes from different sources in post-disaster settings may involve missing elements and inconsistencies, which can severely hamper effective humanitarian decision making. In this talk, we present a new methodological framework based on graph clustering and stochastic optimization to support humanitarian decision makers in analyzing the implications of divergent estimates from multiple data sources on final decisions and efficiently integrating these estimates into decision making. We illustrate the proposed approach on a case study that focuses on locating shelters to serve internally displaced people in a conflict setting, specifically, the Syrian civil war. We use the needs assessment information published by two different reliable sources to estimate the shelter needs in Idleb, a district of Syria. The analysis of data provided by two assessment sources has revealed a high degree of ambiguity due to inconsistent estimates. We apply the proposed methodology to integrate the ambiguous and divergent estimates into the decision making for determining shelter locations in the district. The results highlight that our methodology leads to higher satisfaction of demand for shelters than other approaches such as a classical stochastic programming model. Moreover, we show that our solution integrates information coming from both sources more efficiently thereby hedging against the ambiguity more effectively.

2 - Real-time Disruption Management in Passenger Railways

Gian Tuor, Katrin Hügel, Fabian Leuthold, Harold Tiemessen

Each day train and train crew dispatchers are faced with unexpected and sudden events that make timetables, rolling stock circulation plans and personnel circulation plans infeasible. The task of the train and train crew dispatchers is to reschedule trains and crews such that passenger inconvenience is minimized and working time regulations and operational rules are respected. This is a big challenge, since passenger railways are large and complex dynamical systems and new schedules must be communicated and realized in short time. Current resource management and planning systems can only provide partial support.

In collaboration with two European railway companies, we develop a Decision Support System that allows to combine experience and expert knowledge from train dispatchers with powerful mixed integer programming models. In an iterative procedure, dispatcher and software find good solutions in short time.

In our applied research, we propose a problem decomposition that considers the responsibilities of the various organizations in the passenger railways system and the way how they share information. Another issue of significant practical relevance is the evaluation / comparison of solutions. This is usually hard since dispatchers do not use mathematical models to rate solutions. Yet, they are very strong in comparing solutions. As all humans, they however have difficulties in finding strong solutions in extremely large search spaces. We solve this problem by introducing soft constraints and an elaborated objective function in our MIP model with weights that are configurable and can be learned over time.

Our MIP is currently tested at two European railways for disruptions concerning an unexpected sudden shortage of personnel. Results are very promising.

3 - Cyberattacks as a Markov Decision Problem

Florian Kaiser, Marcus Wiens, Frank Schultmann

Understanding cyberattacks, predicting their proceeding, and the attackers' selection of a specific attack strategy is becoming increasingly important. Currently, cyberattacks are more of a black box than well-understood in many areas. Cyber threat intelligence (CTI) can help to better understand and comprehend cyberattacks. We introduce cyberattacks as a Markov decision problem (MDP) that is analyzed based on a CTI-knowledge graph allowing the analysis of a hacker's decision. A cyberattack can be perceived as a MDP as the defender often cannot react active-ly to an attack (e.g., in case of a lack of awareness or skills) which means that the strategic decisions of a defender can often be neglected, at least in a short-term horizon. The MDP is encoded in a Markov graph as a multi-level threat ontology and subsequently solved via backward induction using the Bellman equation. To develop the Markov graph as a multi-level threat ontology, we fuse data from different CTI vendors. The Markov graph is weighted based on behavioral aspects of attackers (i.e., motivation and incentives) that mitigates limitations aris-ing from over-simplification of those aspects in cyber risk analysis (i.e., illicit motives or malice). Our main contribu-tions to the scientific discourse are (i) the presentation and development of a multi-level threat ontology and (ii) the introduction and analysis of a behavioral cyber MDP. Within our analysis, we show how the formulation of the MDP can be adapted to consider behavioral aspects (i.e., motivation and incentives) and how different mo-tives influence the selection of attack techniques. The work thus contributes to an increased understanding of cyberattacks, at the end of which is the quantitative assessment of the risk of a cyberattack.

■ FA-07

Friday, 8:30-10:00 - 10.91 Grashof-Hörsaal

Uncertainty and Heterogeneity in Long-Term Energy System Planning

Stream: Decision Analysis and Support
Invited session
Chair: *Christoph Weber*
Chair: *Lisa Taruttis*

1 - Quantifying capacity adequacy in energy system modelling through stochastic optimization

Shima Sasanpour

The ongoing climate crisis requires a thorough transformation of our current energy system. Energy system optimization models (ESOMs) can be helpful tools to determine the optimal structure of future energy systems. ESOMs usually optimize the expansion and dispatch of energy systems through a minimization of the total system costs. The obtained energy systems are designed to cover the energy demand at all times for the specific assumptions made within the underlying scenarios. Therefore, already slight deviations in the scenario assumptions can lead to uncovered demand. The uncertainties in the scenario assumptions can be indirectly captured via the requirement for excess generation capacities. However, the amount of these excess capacities is unclear. This study analyzes capacity adequacy by considering uncertainties through stochastic optimization within an ESOM. Different uncertainties within the energy system, such as CO2 prices, total power demand and different weather years are considered and their influence on the energy system is compared. Therefore, a variety of different assumptions for these uncertainties are extracted from literature and included in the stochastic optimization. As a result, the uncertainties with the highest impact on the structure of the energy system are identified and the excess capacities needed are estimated.

2 - Robust planning of a European Energy System under climate uncertainty using Importance Subsampling

Leonie Sara Plaga, Valentin Bertsch

Anthropological climate change will lead to significant changes in climate. These changes can be projected by Global Circulation Models (GCMs) which model the physical properties of the atmosphere. Due to the complexity of the atmosphere, there are many different GCMs

with different results. As all these model results depict a possible development of the European climate, a future energy system should be robust towards the choice of climate scenario. Due to the great number of scenarios, this poses challenges regarding computational time. In this work, we use the results of different climate models to generate input data for an energy system optimization model of the European electricity sector. To reduce the amount of input data, from each climate scenario a set of timesteps is drawn which includes both random timesteps and the timesteps which are most disadvantageous for the energy system. This method is known as Importance Subsampling. Yet, it has only been applied for a single climate variable and to identify single disadvantageous timesteps. We apply the method for all climate variables influencing the energy system and also identify longer timeseries of disadvantageous conditions. Afterwards, a Robust Optimization of the European energy system is run including the Importance Subsampling results for all climate models. The combination of Importance Subsampling and Robust Optimization allows for the consideration of numerous climate model results in the optimization process and ensures robustness of the final solution towards all climate scenarios. By varying the ratio between random and disadvantageous timesteps, the robustness of the overall solution against disadvantageous climate conditions can be tuned and a relation between robustness and costs can examined.

3 - Heterogenous investors in energy system models

Christoph Weber

With the energy transition, the number of generation units is strongly increasing and these are rather heterogenous in technologies and locations. Even within one class like onshore wind energy, decisions on investments will depend on multiple, often not observable factors. Standard energy system models are formulated as linear programs and are therefore prone to penny-switching, i. e. abrupt changes in primal variables when cost or performance parameters pass some thresholds. Unobserved heterogeneity in individual decision making has been in the past dealt with in discrete choice models, notably the seminal logit model. The presentation presents an approach to formulate these decisions as non-linear optimization problems and to combine them using market clearing constraints. This yields a non-linear yet convex optimization problem. A first application investigates the heterogeneity of wind energy investments across Germany based on the novel approach and compares the outcomes to the results of standard LP formulations. It is shown that the regional spread of investments increases when unobserved heterogeneity is taken into account.

■ FA-08

Friday, 8:30-10:00 - 10.50 HS 102

Decisions under uncertainty in electricity markets

Stream: Energy and Environment, sponsored by EnBW

Invited session

Chair: *Emil Kraft*

1 - Electricity price forward curves: Modelling and analysis across exchanges

Stein-Erik Fleten, Marina Dietze, Leif Kristian Falch, Eivind Almeland Rolstad, Alexandre Street, Davi Valladão

We estimate electricity forward curves based on elementary forward prices. This novel semi-parametric structural model (i) explores the non-arbitrage relations between contracts with overlapping delivery periods, (ii) considers a parametric structure for price seasonality and exogenous variables, and (iii) uses non-parametric techniques to extract the remaining inter-temporal and cross-maturity information from data. We address the multi-objective estimation problem by hierarchical optimization. Based on historical data, we show that our model outperforms benchmarks in terms of estimation error for missing data. We also have access to time series of electricity spot price forecasts, allowing analyses of ex-ante risk premia and extrapolation of forward curves.

2 - Optimized market participation of flexible multi-energy systems in balancing-power, day-ahead, and continuous intraday markets

Niklas Nolzen, Alissa Ganter, Nils Baumgärtner, Ludger Leenders, André Bardow

The rising share of renewable energies increases supply uncertainty in the electricity grid. However, to ensure grid-stability, electricity supply and demand have to be balanced at all times. Thus, there is a growing need for system balancing. The continuous intraday market enables balancing the increased uncertainty. On the continuous intraday market, electricity is traded continuously up to a few minutes before delivery. Continuous trading allows market participants to react quickly to electricity supply and demand deviations. After gate-closure, remaining unexpected deviations are compensated with balancing power to maintain grid-stability. For multi-energy systems, flexible capacity is particularly valuable considering the increasing demand for system balancing. The multi-energy system monetizes its flexible capacity either by trading on the continuous intraday market or the balancing-power market in addition to the day-ahead market. Due to different trading deadlines, coordinated bidding is a sequential decision-making process with coupled decisions. The availability of electricity and flexibility traded in one market depends on the commitments to the other markets. Hence, this paper proposes a method for an optimized and coordinated bidding strategy for balancing-power, day-ahead, and continuous intraday market. For this purpose, we employ option-price theory to approximate the revenues of continuous intraday market trading. Afterward, we use stochastic programming to model the sequential decision-making process. A case study for a flexible multi-energy system shows substantial savings by jointly participating in all three markets. Thus, the optimized bidding strategy provides efficient decision support in short-term electricity and balancing-power markets.

3 - Dynamic Hedging of Futures Term Structure Risk for Renewable Power Producers

Nils Löhndorf

Renewable power producers trade futures contracts to hedge price and volumetric risks. Typically, hedge targets are fixed by risk management, and traders buy and sell futures contracts to match these targets. The timing of trades is often based on intuition of traders who manually adjust their positions as liquidity of products changes over time. Model-based approaches to formally guide this decision process are rare due to the mathematical complexity of the decision problem and the randomness of term structure, production volumes, and market liquidity. We cast the problem of dynamically hedging a renewable power portfolio as a multistage stochatic programming problem under a dynamic risk measure. The model accounts for the stochastic movement of the price forward curve, randomness in renewable production, as well as changes in availability and market depth of different futures products over time. We propose an approach based on approximate dual dynamic programming to compute optimal hedging strategies. We show that the model yields better outcomes on the risk-return spectrum than static hedging strategies. In a case study with real company data and price data of EEX power futures, we show how the model can be used to derive dynamic hedge plans that match a company's risk preferences, and how it can support energy traders in selecting futures products on a daily basis.

4 - Using Machine Learning to predict short-term power price at unprecedented levels

Geoffroy Chaussonnet, Pascal Heider

In this paper we propose a methodoloy to predict power spot price on the German Market (EEX) using Machine Learning.

Recently, the power price in Europe drastically increased mainly due to two factors. First, the price of fuels continuously increased between spring 2021 and Dec. 2021, and second, they literally jumped to higher price when Russia invaded Ukraine on Feb. 24th 2022. These two events led to unprecedented power price levels.

Using Machine Learning (ML) models to predict unprecedented levels is cumbersome because it contradicts the essence of the ML principle. In time series forecasting, ML models are calibrated on a data set in order to replicate the same behaviour reflected by the data set. Mathematically speaking, this can be regarded as interpolation. As long as features and targets stay within the same range as in the training data set, ML usually shows outstanding results.

When the features and/or the targets are outside their training range, the problem of forecasting becomes extrapolation, which is poorly handled by ML.

In the current context, as of April 2022, using ML to predict power price may fall in the category of extrapolation. Either the model is trained over Feb-April 2022, which is interpolation trained on too small data set, or the model is trained on a larger time period but fall into extrapolation.

We present here several strategies to handle this situation. The main one is to predict the difference between the spot price and the Price Forward Curve (PFC), which reduces the levels of the quantity to forecast. Also, updating the PFC N-time per day increases the size of the training data set N-fold, hence leading to a richer training database.

Results are shown in terms of backtests over the year 2022.

■ FA-09

Friday, 8:30-10:00 - 10.50 Raum 604

Future energy systems and security of supply

Stream: Energy and Environment, sponsored by EnBW
Invited session
Chair: *Dominik Möst*

1 - Adequate capacity in the German electricity market: current developments and future solutions
Dominik Möst, Christina Wolff, Hendrik Scharf

Stable operation of the electricity system requires adequate capacities. In a meshed European energy system and increasing shares of renewable energies, determining adequate capacity is becoming increasingly challenging. This contribution illustrates different methods for analysing sufficient capacity in the electricity market and examines their differences: The simplest form of analysis is a static view of capacities using simple availability factors. Chance-constrained programming can extend the static view by uncertainty data, e.g., load and renewable feed-in. Highly sophisticated approaches are probabilistic methods, necessitating much more data and a higher modelling effort. Additional to the illustration of methods, a case study on the German energy system is used to illustrate the challenges in the coming years: The phase-out of coal and nuclear capacities reduces secured capacity. Can the expansion of renewable energies compensate for this decline or are other capacities necessary? And which technologies can play a role here? The contribution discusses the question of adequate capacity and the role of technologies in the coming years but also highlights solutions for a decarbonised energy system with a high share of renewables.

2 - The prospect of heat from CHP with green fuels - a comparative analysis for 2035 using the StoOpt framework
Christian Furtwängler

The recent energy crisis in Europe has underlined the importance of a fast replacement of fossil fuels like natural gas by green energy carriers. Especially, combined heat and power (CHP) generation units that are needed for the efficient supply of heat in densely populated areas in Central Europe today are in need of a new perspective for the future. The use of (partly imported) green fuels, e.g. methane or hydrogen originating from electrolysis with green electricity, is one option for CHP systems. A key question, however, is how these plants perform compared to other forms of heat generation such as the direct usage of electricity for heating purposes through e.g. large-scale heat pumps. This contribution thus aims at investigating the cost structure of the CHP system of the future. For this, three price scenarios for the year 2035 are developed: Scenario A is based on the official German grid expansion plan before the crisis, scenario B considers additional investment in renewable electricity as announced by the Easter package of the German government. Finally, scenario C considers a 100 per cent climate-neutral electricity system based on a recent research project by (Dressler et al. 2020). For these price scenarios, different heating portfolio setups are evaluated by using the established stochastic optimization model framework StoOpt (Beran et al. 2022) in order to obtain optimal dispatch patterns. Heat provision costs and possible contribution margins for the different technologies are evaluated for the individual scenarios and the structure of the optimal merit-order of heat is analysed.

3 - Soft-coupling energy and power system models to analyze pathways toward a de-fossilized German transport sector
Danial Esmaeili Aliabadi, Niklas Wulff, Matthias Jordan, Karl-Friedrich Cyffka, Markus Millinger

The transport sector is a major consumer of energy worldwide. Unfortunately, there is no silver bullet to de-fossilize the transport sector due to its intricacy; therefore, many concepts and technologies should be combined to have a noteworthy impact on this hard-to-abate sector. As such, the required diverse set of expertise for making correct decisions cannot be achieved by merely utilizing one model. In this study, we connect multiple datasets and models that employ various methodologies with different purposes to exhibit a pathway to a green transport sector. The extended bioenergy optimization (BENOPTex) and renewable energy mix (REMix) models are coupled iteratively to produce coherent results while considering different sets of constraints. The combined effects of bioenergy and synthetic fuel - using renewable electricity - on the German transport sector are investigated via two scenarios: a reference scenario and a progressive scenario. Two demand models are also used to capture the specificities of the energy demands of the mainly behavior-driven road transportation as well as technology-driven aviation sector. The outcome of the resulted soft-coupled model respects biomass availability, regulatory circumstances, techno-economic properties, and power sector expansion for the production of synthetic fuels.

4 - A long-term generation expansion planning considering emission quotas under multiple uncertainties
Anil Kaya, Steffen Rebennack

We introduce a long-term stochastic power generation expansion planning model, considering multiple uncertainties such as carbon emission, fuel and energy prices. Generation expansion planning model incorporates investment, retirement and operational decisions, emissions quotas, generators capacity bounds, transmission constraints and battery storage systems. The objective is to minimize the total cost including investment and expected operational cost during the long planning horizon. Considering environmental concerns and emissions quotas, the model determines, as investment, retirement and operational decisions, the types of generation technology, the number of power plants to be added into our portfolio or to be removed from our portfolio and their distributions. Generation expansion planning model is defined as a two-stage stochastic mixed-integer linear program, which is solved by Benders decomposition algorithm. The master problem is a deterministic problem that computes investment and retirement decisions whereas the sub-problem is a multi-stage stochastic linear optimization problem, which determines operational decisions under multiple uncertainties with emission constraints. The sub-problem is solved by a stochastic dual dynamic programming (SDDP). To get an efficient Benders optimality cut for the master problem, a new approach is developed to improve the upper bound calculation of SDDP. Using real data, we present a case study for the German power system to illustrate the efficiency of our approach.

■ FA-10

Friday, 8:30-10:00 - 20.30 SR 0.014

Industrial applications

Stream: Logistics
Invited session
Chair: *David Sayah*

1 - How Can the Construction Site Layout Planning Model (CSLP) be Adapted to the Deconstruction of Nuclear Power Plants?
Niklas Braun, Rebekka Volk, Frank Schultmann

Worldwide and especially in Germany many nuclear power plants are shutdown or will be shut down and dismantled in the short future, resulting in complex dismantling projects. The decommissioning of these power plants is not only technically challenging but also demanding from logistical perspective. All activities of component dismantling and material treatments have to be done inside the confined space of the power plant. For this, respective workstations and material storages must be placed and the best transportation routes between them need to be identified. But the connection of some rooms to the rest of the power plant are often only possible via one or two distinct paths leading to an additional challenge. There is a high risk of creating deadlock positions delaying the project progress until they are dissolved. Currently, these scheduling and location tasks are done manually based on the expertise of planers and executers, often resulting in a short-term solution. While there are some well-established

models like the construction site layout planning (CSLP) to plan the placement of workstations and material storages on construction sites, there is no model for an indoor application with high spatial restrictions. To tackle this challenge and to solve the explained tasks, we created a new model based on a layout representation with separated rooms, so it can be used in confined indoor spaces. While the model was designed with power plants in mind, it can be transferred to any similar indoor planning task with a room structure. The model is tested on a case study with 11 rooms and 3 material types. The experiments show that the model produces better solutions than the usual heuristics of manual planners and is especially good at avoiding deadlock positions.

2 - Operational Planning of Excavated Soils Transportation

Nicolas Blandamour

Transport infrastructure or building sites require the movement of large quantities of excavated soils and building materials. The soil extracted from these construction sites can present different degrees of pollution which require treatments in specialized centers. Once the treatment has been completed, the inert soil obtained can be reused as a backfill for earthworks, while the extracted materials such as gravel can be used as raw material for other construction sites. The different trips needed to move these materials coupled with the operational constraints of construction sites and truck carriers lead to a difficult vehicle routing problem. The goal is to create routes that minimize the distance traveled with empty trucks, to both increase the operational efficiency and minimize the carbon impact implied by these moves.

This talk will present how such a problem was solved in a business application developed for a French company proposing services for the construction industry. In a large urban region like the Paris area, several dozens of construction sites are delegating each day the transportation of soils and materials to this company, which becomes responsible for building routes that efficiently link sites and centers using trucks from external carriers. It represents 100 trucks performing 500 loads and traveling a total of about 25 000 kilometers daily.

The resolution of this problem is based on a route generation approach. First, interesting route candidates are generated using an enumeration scheme. Secondly, a combination model is solved using LocalSolver, a generic global optimization solver, to identify the best selection of routes among the candidates. Such an approach presents several advantages which will be discussed during the presentation.

3 - Heavy Plate Production Design in Steel Industry

Philipp Fath, David Sayah, Stefan Nickel

In this talk we describe a real-world heavy plate production design problem (PPD) faced by a steel manufacturing company. This plate production design problem is comprised of designing one or more types of motherplates and placing rectangular order plates onto motherplates. The PPD is a rich 2D guillotine cutting stock problem as it defines a set of practical requirements arising from the production process. Continuous sized motherplates, software and technology restricted cutting patterns and surplus requirements are among these specialized restrictions.

Our solution approach is a heuristic procedure based on column generation. Decomposing the problem generates a motherplate selection problem (MPS) acting as master problem. The resulting pricing problem is a complex knapsack variant, called motherplate design problem (MPD). Furthermore, we improve the computational challenging pricing problem. One acceleration technique is the heuristic decomposition of the general motherplate design problem.

A significant increase in solution quality compared to the existing solution approach can be achieved, especially for difficult instances. Moreover, the presented algorithm is able to solve real-world instances.

4 - Improving Zalando's Warehouse Efficiency by Relocating Items

Anna Melnichenko, Olivier Boure, Paul Fournel, Francisco Madaleno

A warehouse is a facility of storage storage locations, operating equipment, and people resources that handles the incoming flow of items and manages the inside movements between the storage locations to guarantee the just-on-time dispatch of the outgoing flow of goods.

The inner system of the warehouse can be modeled as a simple network consisting of a source node (inbound area), internal nodes (storage locations), sink node (packing and outbound area), and edges between them. When a customer issues an order for a given product, it needs to be decided from which storage location the item should be processed and how to coordinate its movement to the packing area with other items. Moreover, the items can be moved from storage location to storage location to redistribute the load of the storage locations optimally since the storage locations have different capacities and speeds of processing items.

In our work, we study the Item Relocation Problem, which represents the process of modifying the physical storage distribution of items to improve future logistical operations. The problem is a well-known problem within Logistics Algorithms. A holistic approach to solving the problem from inbound to outbound is a complex endeavor. The problem is compounded by the fact that the system is dynamic and the initial setting (an incoming flow and a predicted demand) changes over time. In our work, we compare two different approaches to problem modelization and various algorithms for computing a solution. We use Linear Programming as a first approach, where we optimize for the distribution of single items within the warehouse. The second approach is Flows over Time (also known as Dynamic Flows), where we model movements of items as a flow over the whole network.

■ FA-11

Friday, 8:30-10:00 - 10.50 Raum 602

Decentralized flexibility and electric mobility

Stream: Energy and Environment, sponsored by EnBW

Invited session

Chair: *Hannes Hobbie*

1 - Decentral decision-making for charging intra logistics equipment with excessive renewable energy

Sebastian Scholz, Frank Meisel

Industrial manufacturing needs to use more renewable energy in order to become more sustainable. However, generation of renewable energy is quite volatile and periods of excessive generation might even require feed-in management actions for stabilization of power grids, which result in a loss of renewable electricity. To counteract this, we present an optimization approach that adapts charging decisions of intra logistics equipment to the availability of renewable electricity. Based on the Industrie 4.0-paradigma, we propose a decentral decision-making platform that orchestrates different types of production and intra logistics equipment while integrating a forecast for impending renewable electricity feed-in reduction into the decision-making process. In this talk, we focus on a company's intra logistics in a job shop environment where jobs have to be processed by several machines with job specific machine routings. We present a MIP optimization model with the objective of synchronizing intra logistics charging decisions to the occurrence of excessive renewable energy. The corresponding intra logistics decision variables state in which period and in which processing mode recharging actions take place and define the charging amount. Our simulation based computational experiments use real data in order to benchmark our intra logistics recharging optimization model against well-known static recharging policies. We show that the presented approach is capable to counteract potential renewable energy losses through increased local consumption, which contributes to CO2-reduced sustainable manufacturing.

2 - Energy-Efficient Driving Model by Clustering of GPS Information

Ashkan Mansouri Yarahmadi, Michael Breuß, Ali Sharifi Boroujerdi

We propose a novel approach to model the energy efficiency of driving styles. A unique property of our method is that it relies exclusively on Global Positioning System (GPS) logs obtained during driving. We conjecture that this setting is highly relevant in practice as GPS logs can easily be acquired. Relying on positional data alone means that all derived features from it will be correlated, so we strive to find a single quantity that allows us to perform the energy consumption analysis. To this end we consider a robust variation of the jerk of a movement. We show that this feature is directly related to the energy consumed during driving. We show that our feature of choice outperforms other more commonly used jerk-based formulations, and we discuss the handling of noisy, inconsistent, and incomplete data arising in real-world GPS logs. Our solution strategy relies on an agglomerative hierarchical clustering combined with an L-term heuristic to determine the relevant number of clusters. It can easily be implemented and performs

fast, even on large real-world data sets. Experiments show that our approach is robust against noise and discerns different driving styles concerning energy consumption. Our intention is to design an intelligent systems in hybrid cars, as the control of electric and fuel-based drives as well as the routing of the cars may be optimised with respect to the energy consumption arising by individual driving style. By collecting data from an individual driver one may easily classify the driving style of the person, e.g. also dependent on different areas like motorway or city centre. We conjecture that the results of this work may also help in designing individualised energy-saving car routing schemes for use with any energy source in mobility.

3 - MILP-based Investment decisions in an electric company fleet
Markus Schindler, Lukas Gnam, Markus Puchegger, Christian Pfeiffer

The conversion of vehicles with combustion engines to electric batteries is a key element in efforts to combat the climate crisis. A high interest in the conversion to electric vehicles exists in the corporate sector, since there are tax incentives but also due to combustion Driving bans implemented in more and more European cities. In this paper, a mixed integer linear optimization model is presented which determines the optimal investment decision for an exemplary small Austrian enterprise aiming to switch from fossil-fueled cars to electrical vehicles. Considering the optimization model, investments int charging infrastructure (maximum charging power, vehicle to grid possibility), size of a photovoltaic system and a stationary electrochemical storage are included into the model.. The optimization is done in a quarter hour grid and over a whole year (35.040 time steps). Total costs are used as the objective function for the model here. Due to the size of the plant, both the energy costs and the costs for the maximum purchased power are used for the energy costs. The driving profiles for the vehicles were generated here using eMobpy. The model was formulated in a modular architecture using Python/Pyomo and solved using Gurobi. With the parameters deposited, it can be seen that the vehicle-to-grid applications are currently not economical. If the vehicle-to-grid application is fixed, it becomes apparent that the overall system begins to exploit price fluctuations in the day-ahead price.

4 - Integration of data centres as an active sector within energy systems models
Juan Jerez, Claire Bergaentzlé, Dogan Keles, Juan Gea-Bermúdez

Energy system models are an important tool for studying the relationship between energy supply and demand, and their predictive value depends on their ability to represent future relevant actors that enable potential new interactions within that system. Data centres are expected to become significant energy consumers in certain regions over the next decade, potentially jeopardising the achievement of energy transition goals through rising energy supply costs and carbon emissions. Despite this sustainability risk, data centres could potentially contribute to the energy transition by, on one side, providing extra flexibility through demand-response and, on the other, promoting energy efficiency through the recovery of excess heat. This article describes the development of an extension to the Balmorel energy system model that allows data centres to invest in cooling storage and heat pump technologies for flexible operation and heat recovery, respectively. In this way, data centres can respond to electricity prices, weather conditions and local district heating signals and compete freely with other supply technologies within the energy system. As an example, this article assesses the potential role of data centres in the Danish energy system by 2050. Preliminary results show a shift in investments from energy infrastructure to data centre equipment and that the carbon footprint of data centres can be significantly reduced. The model presented in this article is also suitable for analysing other industries with a similar structure of electricity-generated cooling demand and excess heat production. This model aims to serve as a platform for future testing of policies to promote data centre integration.

■ FA-12

Friday, 8:30-10:00 - 10.50 Raum 701.3

Integrated Network Design for Public Transportation

Stream: Mobility and Traffic
Invited session
Chair: *Rowan Hoogervorst*

1 - Network Design for a Bus Rapid Transit Line Considering Route and Station Attractiveness
Rowan Hoogervorst, Reena Urban, Philine Schiewe, Evelien van der Hurk, Anita Schöbel

In this talk, we look at the network design problem for a new Bus Rapid Transit (BRT) line in the Capital Region of Denmark. While a general outline for the route of the BRT line has already been determined in this problem, the investments made into route segments and stations still have to be decided. The investments in the route segments establish the BRT standard by determining the extent of dedicated infrastructure and thus the traveling time between stations of the line. Investments in the stations, such as the placement of shared bicycles, instead determine the attractiveness of the station within a multi-modal travel setting. Based on available OD travel data, our objective is to maximize the number of travelers who choose to travel by public transport while respecting a maximum budget that is available for investments in each of the municipalities crossed by the BRT line. We develop an optimization model for the resulting problem, investigate its complexity and present the results of our method for the studied BRT line along ring 4 in the Capital Region.

2 - A branch-and-cut algorithm for the dial-a-ride problem with ride and waiting time minimization
Christian Pfeiffer, Arne Schulz

In recent years, several ridesharing providers launched in large cities. In contrast to the standard dial-a-ride problem, these providers focus on the general public. As they are amongst others in competition with taxis and private cars, it is important for them to ensure short travel times for the customers. In this talk, we consider the resulting dial-a-ride problem with ride and waiting time minimization, which minimizes the relative detours of all customers in relation to the earliest point in time the customer can be picked up. Furthermore, we assume time windows for every customer request. We present a branch-and-cut algorithm with several techniques to improve the search. Moreover, we analyze our techniques in a computational study.

3 - Modeling Uncertainty in the Timetable-Based Railway Network Design Problem
Tim Sander, Nadine Friesen, Karl Nachtigall, Nils Nießen

Many European countries plan their railway infrastructure according to long-term timetables. Often infrastructure expansions, as well as new constructions are necessary in the long run to enable this timetable. While both the timetabling process and network design on their own are well covered by research and various optimization models exist, there exists to the best of the authors' knowledge no model which focuses on timetable-based network design. To take this into account, we present the robust network design problem for railway infrastructure under capacity constraints and uncertain timetables. We model this network design problem as a minimum cost flow where the infrastructure costs are minimized such that the uncertain timetables are conductable. Timetables are given by different train rides with a start, a destination, and a respective earliest departure time and latest arrival time. The capacity of the arcs is limited and can be expanded if the capacity constraints cannot be met. To incorporate the uncertainty of the future timetable, we use a scenario-based approach. We define different scenarios with individual departure and arrival times as well as optional trains. The robust optimization then optimizes the network in a way that all scenarios can be operated while minimizing the expansion costs as well as potential penalty costs. Optional trains are implemented in different ways: They can either be set in some of the scenarios where they must be integrated into the routing or they can have penalty costs if they are not scheduled, creating a trade-off between more trains and additional infrastructure costs. The models have been implemented using Gurobi and we compare the results of the robust approaches to each other and to the deterministic model.

4 - The Multi-Stop Station Location Problem
Erik Mühmer, Felix J. L. Willamowski, Miriam Ganz

We introduce the (directed) multi-stop station location problem. The goal is to install stations such that sequences of stops can be traversed with respect to range restrictions that are reset whenever a station is visited. Applications arise in telecommunications and transportation, e.g., charging station placement problems. The problem generalizes several network optimization problems such as (directed) Steiner tree problems. We show strong intractability results of the directed and undirected version under different complexity assumptions. By a transformation from the directed version to shortest path problems we obtain a linear approximation algorithm.

■ FA-13

Friday, 8:30-10:00 - 20.30 SR -1.025

Financial Management II

Stream: Finance
Invited session
Chair: *Julian Schneider*

1 - Alternative Prize Money Distributions for Higher Gender Equity in Sports
Maren Martens, Verena Starflinger

In many sports, women receive less prize money than men. This issue has been discussed extensively over decades. While many people consider different prize structures for men and women as unfair, others argue, e.g., that men attract greater public interest or that the competition is harder among men than among women (in particular, when there participate more men than women).

In this presentation, we focus on the discussion of fairness in the distribution of prize money in endurance sports concerning the severity of the competition. We present two methods to distribute prize money across gender based on the individual performances w.r.t. gender specific records. We suppose these "across gender distributions" to be fair, as they suitably respect that women generally are slower than men. Furthermore, we compare commonly used prize distributions to our across gender distributions, introducing a statistical fairness function. For our investigations, we focus on triathlon, but the results can easily be adapted to any other endurance sports.

2 - Sports Betting vs. Lottery-like Stock Investing: Evidence from Germany
Julian Schneider

Within the framework of Behavioral Portfolio Theory, I assume that investors use the main part of their available funds for long-term oriented capital accumulation in a basic (low aspiration) portfolio layer. In addition, I assume that a minor share of existing funds, that is the high aspiration layer, is used for gambling. In this context, I build several portfolios where the high aspiration layer (or gambling layer) mirrors the performance of three relatively straightforward sports betting approaches or, as an alternative, returns from a portfolio containing lottery-like stocks. Analyzing the performance and characteristics of the overall two-layer portfolios, I find that maintaining a high aspiration portfolio layer which is used for following signals in sports betting does not lead to an overall outperformance. When following sports betting signals and implementing a simple favorite-based strategy, total volatility is reduced while idiosyncratic volatility increases in comparison to the portfolios where the high aspiration layer consists of lottery-like stocks. Investors aiming to increase overall portfolio skewness benefit from undertaking an underdog-based betting strategy. Furthermore, overall market correlation is lower for the portfolios where sports betting returns constitute the gambling layer.

■ FA-14

Friday, 8:30-10:00 - 10.50 Raum 702

MINLP

Stream: Discrete and Combinatorial Optimization
Invited session
Chair: *Sven Mallach*

1 - Solving Mixed Integer Linear Programs (MILPs) Using Inside Ellipsoid Outside Sphere (IEOS) Model
Mohammad Reza Hesamzadeh

In this paper, we present an Inside Ellipsoid Outside Sphere (IEOS) model for solving general Mixed Integer Linear Programs (MILPs). We start with a general MILP and through a proposed mapping, convert it to an IEOS program (IEOSP). We theoretically discuss several interesting properties of our proposed IEOSP. An efficient solution algorithm for IEOSP is then developed. Our computational studies show the promising performance of our IEOS approach as an alternative approach for solving general MILP problems. We also discuss Unit Commitment (UC) problem in power-system engineering as an interesting application area for our IEOSP theoretical developments.

2 - Feasible rounding based diving strategies in branch-and-bound methods for mixed-integer optimization
Stefan Schwarze, Christoph Neumann, Oliver Stein, Benjamin Müller

We study the behavior of feasible rounding approaches for mixed-integer optimization problems when integrated into tree search of branch-and-bound. Our research addresses two important aspects. First, we develop insights into how an (enlarged) inner parallel set, which is the main component for feasible rounding approaches, behaves when we move down a search tree. Our theoretical results show that the number of feasible points obtainable from the inner parallel set is nondecreasing with increasing depth of the search tree. Thus, they hint at the potential benefit of integrating feasible rounding approaches into branch-and-bound methods. Second, based on those insights, we develop a novel primal heuristic for MILPs that fixes variables in a way that promotes large inner parallel sets of child nodes.

Our computational study shows that combining feasible rounding approaches with the presented diving ideas yields a significant improvement over their application in the root node. Moreover, the proposed method is able to deliver best solutions for SCIP for a significant share of problems which hints at its potential to support solving MILPs.

3 - PaMILO: A Solver for Multi-Objective Mixed Integer Linear Optimization and Beyond
Levin Nemesch, Fritz Bökler, Mirko H. Wagner

In multi-objective optimization, several potentially conflicting objective functions need to be optimized. Instead of one optimal solution, a whole set of so called non-dominated points is wanted. Conflicting objectives can be often found in real world decision making, for example economical costs vs environmental impact in infrastructure planning.

One subset of the non-dominated solutions is the set of non-dominated extreme points. Finding this set is in many cases a computationally hard problem. While solvers for similar problems exist, there are none known for multi-objective mixed integer linear programs (MOMILPs) or multi-objective mixed integer quadratic programs (MOMIQPs). We present PaMILO, the first solver for finding non-dominated extreme points of MOMILPs and MOMIQPs. PaMILO provides an easy to use interface implemented in C++17. It solves occurring subproblems employing either CPLEX or Gurobi. Input instances can be formulated in most of the well known file formats and output is written in an easy to read Json format.

PaMILOs approach is an adaption of the dual-benson algorithm for multi-objective linear programming (MOLP). We will present the algorithmic principles of the dual-Benson algorithm. As it was previously only defined for MOLPs, we also describe how it can be adapted for MOMILPs, MOMIQPs and even more problem classes.

4 - Inductive Linearization for BQPs with Linear Constraints - Computational Experience
Sven Mallach

Given a binary quadratic program comprising linear (and possibly quadratic) constraints, the inductive linearization technique may serve as a computationally attractive compromise between the well-known "standard" linearization, and a complete first-level application of the Reformulation Linearization Technique. In many relevant cases, inductive linearizations are more constraint-side compact than the former and provide a continuous relaxation that is at least as tight. Prominent combinatorial optimization problems where this applies are for instance the Quadratic Assignment, the Quadratic Matching, and the Quadratic Traveling Salesman Problem. To complement this theoretical basis, light is shed on the computational utility of inductive linearizations when combined with a MIP solver and applied to further example problems and established benchmark instances.

■ FA-15

Friday, 8:30-10:00 - 10.50 HS 101

Remanufacturing, Rework, and Retrials

Stream: Supply Chain Management
Invited session
Chair: *Danja R. Sonntag*

1 - Inventory control in production-inventory systems with random yield and rework

Danja R. Sonntag

A single-stage make-to-stock production-inventory system under random demand and random yield is considered, where defective units are reworked. We examine how to set cost-minimizing production/order quantities in such imperfect systems, which is challenging because a random yield implies an uncertain arrival time of outstanding units and the possibility of them crossing each other in the pipeline. To determine the order/production quantity in each period, we extend the unit tracking/decomposition approach, considering the possibility of order-crossing, which is new to the literature and relevant to other planning problems. The numerical study reveals that a proposed state-dependent policy can reduce inventory-related costs compared to the base-stock policy by up to 6% and compared to an existing approach from the literature by up to 4.5%. From a managerial perspective, the most interesting finding is that a high mean production yield does not necessarily lead to lower expected inventory-related costs.

2 - The Role of Part Failure Rates Asymmetry and Proprietariness of Components on Remanufacturing Decision Making

Rainer Kleber, Joao Quariguasi Frota Net, Marc Reimann

Sourcing affordable replacement parts is a major issue in the secondary market. Independent remanufacturers (IRs) claim that this problem is aggravated by having products with proprietary parts showing high relative failure rates, e.g., a washing machine that, when collected for remanufacturing, almost always contains a defective PCB board. At the same time, all other components being functional makes scavenging for parts a challenging option. In this paper, we examine this claim. Using a stylized model and starting with a setting without proprietary parts, we observe that a high part failure rate asymmetry does not necessarily lower IR profitability. We also find that strongly asymmetric relative failure rates might increase both collection and remanufacturing. We extend our results to examine the impact of part failure rate asymmetry on remanufacturing decisions for products containing proprietary parts. Our results are structurally identical. Yet, the existence of proprietary parts always leads to less remanufacturing, while the collection may increase. Interestingly, an increase in the proprietary content of the product can benefit the IR in certain settings. For policymakers invested in promoting remanufacturing, our results pose important trade-offs on the interplay between part proprietariness and the part failure rates asymmetry.

3 - Firefly Algorithm for Cost Optimization of FM/FM/1/WV Retrial Queue with Catastrophes

Sibasish Dhibar, Madhu Jain

This investigation deals with the performance analysis and cost optimization of the Markovian retrial queueing model in a generic setup by incorporating the working vacation and customers' discouragement behaviour. The server rendering service to the customers is subject to breakdown and can be recovered after getting the repair. The governing system of difference equations has been framed to derive the steady-state probabilities of the queueing model. Using probability generating functions and difference equation theory, we present a simple alternative to carry out the entire analysis in this research work. The queue length distributions and various performance indices are obtained explicitly. The fuzzified parameters are used to develop the fuzzy FM/FM/1/WV model. To determine the optimal design parameters, the cost minimization problem has been solved using the firefly algorithm and quasi-Newton's method. The suitable illustration is taken for both crisp and fuzzified models to facilitate the numerical results of performance indices and optimal service rates.

4 - Solving the Continuous Capacitated P-Median Problem using GRASP and VNS

Abdulaziz Alageel, Martino Luis, Shuya Zhong

There are economic impacts on how the network of facilities is designed and allocated to serve the customers through their daily operations. While there may be a variation in the influence of the impacts due to the location of the facilities, immediate attention to the influence of the effects before choosing a facility location has created little interest in the facility location decision studies. This study evaluates the location-allocation problem for a network of facilities that produce the product and need a suitable location where the customers' demand can be satisfied maximumly multisource continuous capacitated p-median problem (CCPMP). The aim is to minimize the distance between the p facilities and the point of demand. Therefore, there are two metaheuristic ways of solving this CCPMP. This research will use the greedy randomized adaptive search procedure (GRASP) method that generates high-quality computation in a short period and the variable neighborhood search (VNS) that provides quality solutions for the CCPM. The overall performance of the proposed methods is estimated using the datasets from the literature.

■ FA-16

Friday, 8:30-10:00 - 20.30 SR -1.012

Nonconvex Optimization Problems

Stream: Continuous and Global Optimization
Invited session
Chair: *Mathias Staudigl*

1 - A Gauss-Newton-based Decomposition Algorithm for Nonlinear Mixed-Integer Optimal Control Problems

Clemens Zeile, Adrian Bürger, Angelika Altmann-Dieses, Sebastian Sager, Moritz Diehl

For the fast approximate solution of Mixed-Integer Non-Linear Programs (MINLPs) arising in the context of Mixed-Integer Optimal Control Problems (MIOCPs) a decomposition algorithm exists that solves a sequence of three comparatively less hard subproblems to determine an approximate MINLP solution. In this work, we propose a problem formulation for the second algorithm stage that is a convex approximation of the original MINLP and relies on the Gauss-Newton approximation. We analyze the algorithm in terms of approximation properties and establish a first-order consistency result. Then, we investigate the proposed approach considering an illustrative numerical example of Mixed-Integer Optimal Control (MIOC) of a simple nonlinear and unstable system and considering a more complex application that is a numerical case study of MIOC of a renewable energy system. The investigation shows that the proposed formulation can yield an improved integer solution regarding the objective of the original MINLP compared with the Combinatorial Integral Approximation (CIA) algorithm.

2 - On a Computationally Ill-Behaved Bilevel Problem with a Continuous and Nonconvex Lower Level

Yasmine Beck, Martin Schmidt, Johannes Thürauf, Daniel Bienstock

It is well known that bilevel optimization problems are hard to solve both in theory and practice. We highlight a further computational difficulty when it comes to solving bilevel problems with continuous but nonconvex lower levels. Even if the lower-level problem is solved to epsilon-feasibility regarding its nonlinear constraints for an arbitrarily small but positive epsilon, the obtained bilevel solution as well as its objective value may be arbitrarily far away from the actual bilevel solution and its actual objective value. This result even holds for bilevel problems for which the nonconvex lower level is uniquely solvable and its convex constraint set satisfies Slater's constraint qualification for all feasible upper-level decisions. Since the consideration of epsilon-feasibility cannot be avoided for nonconvex problems, our result shows that computational bilevel optimization with continuous and nonconvex lower levels needs to be done with great care.

3 - Solving Copositive Optimization Problems using Outer Approximations of the Copositive Cone

Markus Gabl, Kurt Anstreicher

It is well known that many interesting hard problems, such as a broad class of nonconvex quadratic optimization problems and certain adjustable robust optimization problems, can be exactly reformulated as copositive optimization problems that are convex but involve copositive cone constraints, which are difficult that handle. We consider the solution of such copositive optimization problems using an outer approximation of the copositve cone that is iteratively strengthened with conic constraints and cutting planes. Our methodology utilizes computationally efficient MIP-based oracles for the copositive cone and some generalizations of that cone. In numerical testing we are able to solve a variety of copositive problems to optimality.

4 - Hessian-barrier algorithms for non-convex optimization

Mathias Staudigl, *Pavel Dvurechensky*

We consider the minimization of a continuous function over the intersection of a regular cone with an affine set via a new class of adaptive first- and second-order optimization methods, building on the Hessian-barrier techniques introduced in Bomze, I. M., Mertikopoulos, P., Schachinger, W., & Staudigl, M. (2019) SIAM Journal on Optimization, 29(3), 2100-2127. Our approach is based on a potential-reduction mechanism and attains a suitably defined class of approximate first- or second-order KKT points with the optimal worst-case iteration complexity for first and second order schemes, respectively. A key feature of our methodology is the use of self-concordant barrier functions to construct strictly feasible iterates via a disciplined decomposition approach and without sacrificing on the iteration complexity of the method. To the best of our knowledge, this work is the first which achieves these worst-case complexity bounds under such weak conditions for general conic constrained optimization problems.

■ FA-17

Friday, 8:30-10:00 - 20.30 SR -1.011

Decision Support Systems

Stream: Health Care Management
Invited session
Chair: *Michael Moos*

1 - Multi-objective optimisation for constructing cyclic appointment schedules for elective and urgent patients

Tine Meersman

We study the construction of a cyclic appointment schedule in an outpatient department. We determine the capacity distribution between elective and urgent patients and the scheduling of time slots reserved for these patients such that the waiting times of patients are minimised. The proposed methodology devises a Pareto set of cyclic schedules based on these waiting times with different capacity allocations. An approximation of the Pareto set of non-dominated schedules is obtained using a multi-objective archived simulated annealing heuristic. To accurately validate the cyclic appointment schedules, we incorporate operational decision-making via scheduling individual patients. To this end, we simulate operational variability, i.e., patient arrivals, no-show behaviour, punctuality and scan durations. Patients are assigned one-by-one using an online scheduling rule. Computational experiments are conducted with a real-life case study. We compare different appointment scheduling rules and discuss the impact of the capacity distribution between elective and urgent patients and the timing of urgent slots. The results show that the distribution of capacity between patient types, the timing of urgent slots and appointment rules all have significant impacts on patient waiting times. Appointment waiting times improve when urgent slots are spread equally over and throughout the days and when the Bailey-Welch rule is used. Trade-offs between elective and urgent waiting times resulting from different capacity distributions or slot timing are exemplified via a Pareto front. The proposed method outperforms relevant single-pass methodologies, and we demonstrate that its performance is strengthened thanks to the integrated optimisation of strategic, tactical and operational decisions.

2 - Timeslot allocation for waiting list control

Theresia van Essen, *Yanna van der Vlugt*, *Mijke Carlier*

Patients visiting a hospital for elective surgery often have multiple consultations of different types with a surgeon before undergoing surgery. Hospital make a schedule several weeks in advance where outpatient department timeslots are allocated to these different consultation types. Changing the proportion of consultation types affects the patient waiting lists for both consultations and surgery. However, the precise consequences of such interventions are uncertain, as not all patients follow the same treatment pathway. Furthermore, as these planning decisions are made far in advance, they are based on an uncertain prediction of future waiting lists. The goal is to use these interventions to control waiting lists, in order to reduce waiting times for patients and to ensure that all available time capacity in the outpatient department and operating room is used. The problem is modelled as a Markov decision process (MDP). As the state space is very large, the problem does not admit an exact solution. Therefore, least-squares policy iteration is used to find an approximate solution. We also formulate an (integer) linear program which is used to solve a deterministic variant of the MDP, and investigate some simple decision rules. The solution methods are tested on a case study at a hospital in the Netherlands. Based on a simulation study, we find that all methods improve on the static roster method used by the hospital, with the linear program leading to the best results.

3 - Web-based prevention and treatment of adjustment disorders after life-threatening cardiovascular events

Oliver Werth, *Nurefsan Demirbuga*, *Michael H. Breitner*

Many patients develop psychological disorders after life-threatening cardiovascular diseases, such as adaptation disorders, brooding, and depression. Past studies indicate that approximately 28.4 % of cardiological patients have an additional psychological disorder. However, not every patient has quick access to this effective psychological therapy, resulting in long waiting times for professional psychological care. The transfer of a previously offline therapy to treat adjustment disorders for patients with preexisting cardiovascular diseases into an online solution may be a possible approach for faster access to psychological care. We propose "LeA" (Learn Attention), a web application, and tested it with a larger number of patients (n=12) with cardiovascular diseases. Patients could view and perform the associated exercises and techniques using the web application created with their mobile devices, e.g., tablet computers. We conducted semi-structured interviews and performed survey-based research to receive feedback and suggestions for improvement for LeA. The results of this feasibility study are presented. From an academic point of view, we shed light on critical acceptance factors of patients towards digital solutions, i.e., web-based prevention and treatment of adjustment disorders after life-threatening cardiovascular events. The implications are faster, first access to psychological care for new patients. Existing patients can integrate psychological therapy into their daily lives and their existing face-to-face sessions, perform regular exercises, and thus, increase their psychological well-being.

4 - Digitally assisted resilience building

Michael Moos, *Alexander Scherrer*, *Tobias Zimmermann*, *Lisa von Boros*, *Donya Gilan*, *Isabella Helmreich*, *Friederike Koehler*, *Sarah Schaefer*, *Oliver Tuescher*, *Tabea Werner*, *Michele Wessa*, *Federico Zappala*

Psychological stresses such as private problems, occupational stress or difficult life circumstances, as in the Corona pandemic, can have serious effects on mental or physical health. An effective preventive approach against such health consequences is to strengthen personal resistance to psychological stress (resilience). Because of the widespread prevalence of such stresses in the population, resilience building should ideally be accomplished with a widely available prevention service that can be provided and operated with few resources from already limited professional staff. This research presents a solution approach for digitally assisted training of the personal resistance to psychological stress. Resilience building is treated as a multi-objective sequential decision problem including gamification aspects based on a knowledge-based system. The personal resilience profile in the different resilience factors is created via associated questionnaires using comparative data. This provides a solid data basis for qualified decision making. Based on this multi-criteria assessment and the current training status, individually suitable training content is determined from a knowledge base. Decision-making is thus based on suitably prepared profound expert knowledge. The selection of suitable training content is made by evaluating the respective prerequisites on the resilience profile and training level using a rule-based system. The step-by-step change of resilience profile and training level is addressed by sequential decision making. The execution of the training content is promoted by using gamification concepts. The solution approach was implemented and made available as a prototypical web service with evaluations and training content for the population of Germany.

■ FA-18

Friday, 8:30-10:00 - 20.30 SR -1.013

Markets and Production Systems

Stream: Simulation
Invited session
Chair: *Stefan Wolfgang Pickl*
Chair: *Maximilian Moll*

1 - A Dynamic Utility Threshold Policy in Centralized Matching Market

Shuoqiang Zeng

I consider a matching market where buyers and sellers arrive according to independent distributed Poisson processes with same mean. In this market, utility occurs when buyers and sellers are matched, while cost arises when they wait; the optimization goal is to maximize the welfare, which is defined as utility minus cost.

In the aforementioned market, matching policy is a hyperparameter, affecting significantly the key indexes of the market, such as average waiting time, welfare rate and fraction abandoned. A dynamic utility threshold matching policy is designed in which matching occurs when the utility of the matching exceeds the threshold, and this threshold for each matching pair is dynamic, determined by a given instantaneous threshold function with an initial threshold value and the waiting time of two agents as its parameters. I use two methods to analyze the performance of static utility matching policy and the dynamic policy with the same initial threshold value. One method is theoretical comparison in terms of the expected welfare of a single achieved match and the effect of the number of matches made on the model state, while the other is numerical in terms of welfare rates. The results prove that the aforementioned dynamic policy has its advantage when the relationship between waiting cost and waiting time is non-linear, despite externalities to subsequent matches exist.

2 - GTRF: Generalized Trade Reduction Framework for Double-Auction Mechanisms

Jacob Ehrlich, Maximilian Moll, Stefan Wolfgang Pickl

In a groundbreaking paper McAfee introduced the Trade Reduction (TR) Mechanism that circumvents the famous Myerson and Satterthwaite impossibility result by sacrificing a small amount of efficiency. Here the author creates order statistics based on the submitted bids and reduces at most the least efficient trade. Based on this principle an alternate mechanism was proposed by Segal-Halevi et al. which extends this to the strongly budget balanced setting. This paper proposes a generalization of these two TR mechanisms to fit into a larger framework that can be implemented based on the market in which the auction is to be applied. Additionally, by taking advantage of the relationship of bid order-statistics a novel mechanism is revealed to complete GTRF. Using a simulation based evaluation, performance is characterized across various settings in order to achieve optimized results.

3 - Simulation-Based Optimization of Lot Sizes for stochastic multi-item and multi-stage Production Systems with Rolling Horizon Planning

Wolfgang Seiringer, Manuel Schlenkrich, Sophie Parragh, Klaus Altendorfer

Optimizing lot sizes is a crucial step in production planning due to the effects on the production schedule and key process indicators. Customer demand is usually uncertain and updated periodically, which makes the lot sizing problem more complex. To tackle the issue of uncertain demand, stochastic and robust optimization are known approaches that can be integrated into production system planning. However, with an increasing planning horizon, the mathematical programming formulations for these optimization approaches become very large and computationally hard to solve. For production systems with stochastic influences, event-based simulation can be applied to model production planning like material requirements planning (MRP). We develop a simulation-based optimization framework that integrates two-stage stochastic programming and budget-uncertainty robust optimization into an event-based simulation environment replicating a stochastic production system. In order to counteract the increasing complexity of the optimization models and to address the issue of periodically updated demand, we split the planning horizon into smaller sub horizons. We then solve the optimization models for the sub horizons in a rolling horizon setting using updated information on demand and current production system state provided by the simulation environment. This approach allows to consider uncertain customer demand and resource capacity and is expected to overcome the limitations of static lot size optimization. We investigate different production system structures including multiple production stages and perform a simulation study to evaluate the production system performance of the presented simulation-based optimization approach compared to standard MRP.

4 - A simulation-optimization approach for a stable production scheme in a tablets packaging process

Michael Simonis, Stefan Nickel

This paper discusses an iterative simulation-optimization approach to estimate high-quality solutions for the capacitated lot-sizing problem with linked lot sizes and backorders (CLSP-L-B) based on probabilistic demands. An uncertainty framework for incorporating the impact of simulated demand scenarios is embed-ded into the CLSP-L-B. The framework is generalized by a variable neighbor-hood search (VNS) approach, which accelerates the search for stable production schemes. Moreover, an exact mathematical problem formulation is introduced for a generalized version of the model framework. Anonymized real-world data of four tablets packaging robots is used for evaluation. The experimental design co-vers nine classes of demand uncertainty per packaging robot. Additionally, pro-posed solutions are evaluated against an established benchmark approach from literature for each uncertainty class in terms of manufacturing costs and customer service levels. Finally, planning rules and managerial insights are given for the packaging robots.

■ FA-19

Friday, 8:30-10:00 - 20.30 SR 0.019

Engineering Tools

Stream: OR in Engineering
Invited session
Chair: *Philipp Seufert*

1 - Design of Experiments under Uncertainty: Concepts, Suitability and Solution via an Adaptive Discretization

Philipp Seufert, Jan Schwientek, Karl-Heinz Küfer

In optimal experimental design (OED) one searches for experiments which optimize parameter precision. This is typically done by optimizing a function (design criterion) of the Fisher information matrix. However, the underlying model, and thereby also the Fisher information matrix, often depend on uncertain parameters. These can be, but are not limited to, the unknown model parameters. In applications it is of great interest to find robust designs, which provide extensive information on the unknown parameters, even under varying values of the uncertain values.

In the literature a variety of robustness concepts have been applied to OED, including average-case, worst-case and conditional value at risk. However, the resulting problems in general are non-convex infinite dimensional problems and thus cannot be solved to global optimality. We discuss how to adapt the uncertainty concepts, mainly utilizing the entropic smoothing, and present reformulations as bi-level convex problems, which are closely related to semi-infinite programming. The bi-level problems can then be solved via an iterative algorithm which adaptively discretizes the design space and has finite dimensional subproblems.

Accompanied by an example from chemical engineering we compare the resulting methods and solutions. We discuss performance of the methods as well as quality of results with respect to hedging against uncertainty.

2 - Robust Container Scheduling

Florian Roland Breda

Container logistics plays an important role in the globalized world to transport consumer goods in standardized ways. In this paper we deal with the transportation of containers by cranes as it is practiced at ports. The plans that determine the sequence of container loading are usually planned only under optimal conditions, which rarely exist in reality. We investigate the influence of occurring delays in the transport of containers on the planning made and its influence on the total processing time required. For this investigation, a comparison of a deterministic model with our approach of a robust multilevel optimization model is performed to find out under which conditions our approach generates better plans compared to the deterministic model.

■ FA-20

Friday, 8:30-10:00 - 20.30 SR 0.016

Dynamic Pricing

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

1 - Intertemporal Pricing for Multiple Resources

Kristina Bayer, Robert Klein

In this talk, we address a service provider's intertemporal pricing problem for renewable and substitutable resources, such as hotel rooms of different categories for several periods. For each combination of resource and period, a static price has to be selected from a pre-defined set such that the total revenue is maximised. The availability of these renewable resources is restricted due to capacity constraints in each period. In a selling period consumers arrive, that differ from one another with respect to the intervals (of periods) they are interested in and their willingness to pay for such an option, i.e. a certain combination of interval and resource. In the event of a purchase, a customer chooses the option that maximises her consumer surplus. We further consider restrictions on prices such as a maximum number of price changes. As a consequence, not every matrix of prices is feasible. Even if the number of consumers, the sequence of their arrival, and their individual reservation prices are known, the selection of optimal prices is computationally expensive. Capacity constraints may cause dynamic substitution forcing customers to switch from their preferred options to others. We propose several heuristic algorithms for the described problem. These heuristics are able to deal with different restrictions on prices, one of the heuristics uses a MIP to regain feasibility. We also present first computational experiments.

2 - Nonlinear Dynamic Pricing in the Presence of Multiunit Demand

Rouven Schur

Enabled by technological developments, dynamic pricing is gaining more importance in other fields than the airline industry. Thereby, it encounters new scenarios where neglecting multiunit demand leads to suboptimal prices and lost revenues. Whenever there is a finite stock and selling horizon as well as multiunit, stochastic, and price sensitive demand, a combination of dynamic and nonlinear pricing might be helpful to maximize expected revenue or profit.

We consider a firm that is monopolistic and can price-discriminate between different order sizes by quoting batch prices. To reflect customers' decision regarding batch size, we adapt an adequate customer choice model based on random willingness-to-pay. Due to complexity of the optimization problem, we introduce two heuristics to solve the optimization problem approximately. We test both heuristics in a simulation study against an upper bound and analyze some patterns in the corresponding policies.

3 - A Conceptual Framework for Studying Self-Learning Agents in Recommerce Markets

Rainer Schlosser, Alexander Kastius

In many markets, retailers as well as customers look for an increased sustainability. Recommerce markets – which offer the opportunity to trade in and resell used products – are constantly growing and help to use resources more efficiently. To additionally manage the trade in and resell prices is challenging for retailers as substitution and cannibalization effects have to be taken into account. An unknown heterogeneous customer behaviour as well as competition with other merchants regarding both sales and buying back resources further increases the problem's complexity. Data-driven pricing agents offer the potential to find well-performing strategies and satisfy the need for automated decision support, particularly in online markets. As the training of such agents is typically data hungry and too costly to be performed in practice synthetic test environments are needed to try out and evaluate self-learning pricing agents in different market scenarios. In this paper, we propose a conceptual approach for such a market simulation framework and its basic components. Further, we discuss requirements and opportunities to study self-learning pricing strategies in Recommerce markets.

4 - Multi-Agent Dynamic Pricing Using Reinforcement Learning and Asymmetric Information

Alexander Kastius, Rainer Schlosser

Self-learning agents can be used in numerous ways for dynamic pricing nowadays. It has been shown, that reinforcement learning can serve as a toolkit to efficiently develop pricing strategies in dynamic environments. In many real-world situations, it can be expected that not just a single market participant relies on such tools to implement pricing processes. Instead, a more realistic setting would include multiple self-learning agents. As an agent with varying strategies violates the Markov property, this combination of tools tends to lead to market situations in which equilibria with stable strategies are hard to achieve. Past publications proposed to rely on asymmetric information to achieve equilibria, for example by searching for Stackelberg equilibria. Those usually focused on tabular solutions or solvers to find those equilibria. We propose to merge those concepts with the now available function approximation tools for high dimensional state spaces by exchanging policy information between multiple actors. We aim to allow convergence towards stable policies even in settings with multiple self-learning agents. We discuss possible problems and their solutions and propose a simulation environment for further evaluation of the developed system.

■ FA-21

Friday, 8:30-10:00 - 30.96 Seminarraum 1. OG (R104)

Auctions and Markets

Stream: Game Theory and Behavioral Management Science
Invited session
Chair: *Maximilian Fichtl*

1 - Computing Bayes Nash Equilibrium Strategies in Auction Games via Gradient Dynamics

Maximilian Fichtl, Matthias Oberlechner, Martin Bichler

Auctions are modeled as Bayesian games with continuous type and action spaces. Computing equilibria in auction games is computationally hard in general and no exact solution theory is known. We introduce algorithms computing distributional strategies on a discretized version of the game via convex online optimization. One advantage of distributional strategies is that the expected utility of agents is linear in the strategies. It follows that if our regularized optimization algorithms converge, then they converge to an approximate equilibrium of the discretized game with high precision. Importantly, we show that the equilibrium of the discretized game approximates an equilibrium in the continuous game. In a large number of experiments, we provide empirical evidence that the method approximates the analytical (pure) Bayes Nash equilibrium closely in a wide variety of auction games, often within a few minutes. This is remarkable, because in many finite games learning dynamics do not converge or are even chaotic. When agents are symmetric, we find equilibria in seconds. The method allows for interdependent valuations and different types of utility functions and provides a foundation for broadly applicable equilibrium solvers that can push the boundaries of equilibrium analysis in auction markets and beyond.

2 - Approaching the Overbidding Puzzle in All-Pay Auctions: Explaining Human Behavior through Bayesian Optimization and Equilibrium Learning

Markus Ewert, Stefan Heidekrüger, Martin Bichler

It is an established fact in behavioral economics that in lab experiments of auctions, human subjects do not adhere to the risk-neutral Bayesian Nash equilibria of such games. Several attempts at explaining this Overbidding Puzzle focus on the bidders' psychology and suggest they may have parametrized utility functions that differ from the risk-neutral payoff. However, analytical equilibria of the resulting modified games are generally not available. Consequently, it has been difficult to identify the specific parameters and assess the merits of these proposed modifications in explaining empirical observations. With recent advances in equilibrium learning, it has become tractable to compute approximations of Bayesian Nash equilibria. Building on these advances and Bayesian optimization, we propose a novel regression framework to infer unobserved parameters of Bayesian games from behavioral data. We apply our method to two data sets of human bidding behavior in all-pay auctions. For the first time, this makes it possible to directly compare the goodness-of-fit of several proposed qualitative explanations of overbidding.

3 - Considering Short and Long Term Fairness in Recurrent Auctions

Sebastian Velten, Till Heller

Fairness concepts play a crucial role in the design of auction mechanisms. A well-known approach is the Vickrey-Clarke-Groves (VCG) mechanism, in which truthful bidding is an optimal strategy. Since this fairness concept is limited to a specific auction run, a VCG mechanism can only guarantee short-term fairness. However, if the same group of players participates in auctions more frequently, past auction results also have an impact on the 'fairness' of the mechanism, i.e. the fraction of accepted and submitted bids should be as equal as possible in the long run. In this paper, we present a bicriteria optimization problem that contrasts short-term fairness and long-term fairness to obtain an auction mechanism that attempts to find solutions that consider each fairness concept. The underlying winner determination problem (WDP) for both fairness concepts is modeled as a variant of the hitting set problem (HSP). In this problem, we consider sets of bids that cannot be winning at the same time and, therefore, try to select losing bids in each of the sets.

We apply this approach of iterative auctions to a cooperative rostering problem in which employees bid on free time slots. As in rostering problems various constraints like staff requirements or minimum rest times must be respected, it is generally not possible to accept all bids (wishes for free time) in a planning period and short-term as well as long-term fairness are important. For this case study we analyze the properties of the resulting solutions over several planning periods.

4 - Core-Stability in Assignment Markets with Financially Constrained Buyers

Martin Bichler, Eleni Batziou, Maximilian Fichtl

We study markets where a set of indivisible items is sold to bidders with unit-demand valuations, subject to a hard budget limit. Without financial constraints and pure quasilinear bidders, this assignment model allows for a simple ascending auction format that maximizes welfare and is incentive-compatible and core-stable. Introducing budget constraints, the ascending auction requires strong additional conditions on the unit-demand preferences to maintain its properties. We show that, without these conditions, we cannot hope for an incentive-compatible and core-stable mechanism. We design an iterative algorithm that depends solely on a trivially verifiable ex-post condition and demand queries, and with appropriate decisions made by an auctioneer, always yields a welfare-maximizing and core-stable outcome. If these conditions do not hold, we cannot hope for incentive-compatibility and computing welfare-maximizing assignments and core-stable prices is hard: Even in the presence of value queries, where bidders reveal their valuations and budgets truthfully, we prove that the problem becomes NP-complete for the assignment market model. The analysis complements complexity results for markets with more complex valuations and shows that even with simple unit-demand bidders the problem becomes intractable. This raises doubts on the efficiency of simple auction designs as they are used in high-stakes markets, where budget constraints typically play a role.

■ FA-22

Friday, 8:30-10:00 - 20.30 SR -1.008 (UG)

Rigorous Results for Heuristics, Metaheuristics and Matheuristics

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *John Warwicker*

1 - Time-complexity analysis of co-evolutionary algorithms

Mario Hevia Fajardo, Per Kristian Lehre

Co-evolutionary algorithms are simple general-purpose optimisers used to solve complex problems for which no objective function for evaluating potential solutions is present or known. Instead, a payoff function is used, such that the objective value of a solution depends on actions of some adversary or adversaries. These algorithms use one or more populations of solutions that mimic natural co-evolution of species by iteratively applying evolutionary operators such as mutation, recombination, and selection to improve the current solutions. Because of the complex interactions that arise between the populations of solutions, these algorithms are poorly understood and applications are often limited by pathological behaviour, such as loss of gradient and cyclic non-convergent behaviour.

It is an open challenge to develop a theory that can predict when co-evolutionary algorithms find solutions efficiently and reliably. This talk describes time-complexity analyses that have provided a better understanding of how co-evolutionary algorithms behave throughout the optimisation.

2 - Replicability and Reproducibility in Metaheuristics and Matheuristics Research

Manuel López-Ibáñez, Juergen Branke, Luis Paquete

Research on Metaheuristics and Matheuristics often relies on experimental studies to support scientific claims. However, published results are sometimes neither replicable nor reproducible due to missing critical experimental and implementation details and the unavailability of datasets, problem instances, and source codes. This talk will introduce a clear terminology for discussing various levels of reproducibility ("repeatability", "reproducibility", "replicability" and "generalisability") that further refines the definition provided by the Association for Computing Machinery (ACM). We will discuss the importance of reproducibility and current technical and cultural obstacles for achieving it. Finally, we will suggest practical guidelines for enhancing the reproducibility of your own research.

3 - A hybrid metaheuristic for the clustered travelling salesman problem

Abtin Nourmohammadzadeh, Stefan Voss

In this work, a special type of the travelling salesman problem (TSP), namely, clustered TSP (CTSP) is addressed. In the CTSP, there are a number of clusters and each city belongs to one of them. The salesman seeks to find the shortest tour through all the cities which includes each city exactly once while being restricted to visit the cities of each cluster directly after each other. A hybrid metaheuristic consisting of the artificial bee colony (ABC) and the tabu search (TS) algorithm is proposed to deal with the problem. The results of our solution approach on two sets containing random and benchmark instances are presented and compared with those of two other methods.

Friday, 10:30-11:30

■ FB-01

Friday, 10:30-11:30 - 30.95 Audimax A & B

Semi-plenary talk Pickl

Stream: PC Stream
Semi-plenary session
Chair: *Wolf Fichtner*

1 - 50 Years Club of Rome - OR Challenges and Perspectives on Energy Security and Complex Resource Conflicts
Stefan Wolfgang Pickl

2022 is a special year from different perspectives. Resource conflicts, security, and climate-policy issues play an important role. This talk summarizes the history of 50 years of the Club of Rome and presents personal views from Operations Research on complex resource conflicts and scenario-based decision-making processes in the context of energy security.

Different mathematical decision models and solution concepts are presented. The TEM model is summarized and a game-theoretic extension is discussed. An algorithmic solution concept based on intelligent optimization techniques is derived. Some generalizations are characterized.

In the future, managerial decision-making will be influenced by certain developments of AI-based expert systems, machine learning techniques, as well as various reinforcement learning approaches. Prescriptive analytics could be considered as an example of how managerial decision-making could be seen as a further application for control science and classical optimization in the context of energy security and complex resource conflicts.

Can intelligent optimization lead to sustainable solutions . . . ?

This contribution is dedicated to Ernst Ulrich von Weizsäcker, Honorary President of the International Club of Rome.

■ FB-04

Friday, 10:30-11:30 - 10.11 Hertz-Hörsaal

Semi-plenary talk Lurkin

Stream: PC Stream
Semi-plenary session
Chair: *Oliver Grothe*

1 - Moving Consumer Goods, Not Vehicles
Virginie Lurkin

The Vehicle Routing Problem (VRP) is certainly the most widely studied combinatorial optimization problems within the transportation research community. Simply defined it aims at finding the least cost delivery routes to visit a set of geographically dispersed customers. A very large variety of formulations and solutions methods have been proposed since Dantzig and Ramser pioneered the field in 1959.

Over the last decade, the ever-accelerating trends of e-commerce and urbanization led the logistics community to define rich routing problems, embedding new attributes to better represent real-world environments. Although the objective of smooth and seamless flow of goods in urban areas remains, more sophisticated VRP formulations have been introduced to capture the complexity of existing problems more accurately. Well-known examples are the inclusion of environmental concerns or uncertain traffic conditions.

While all VRPs require demand data as input, the logistics community has mainly focused on the operational objective and constraints of the supplier, whereas the behavior of the consumers has been traditionally implicitly addressed in the planning process. This is still the case for most rich VRP. Aggregation or simplifying assumptions are made on the demand side. In this talk, I discuss how disaggregate demand representations allows to better account for the heterogeneous preferences of the customers (for example regarding delivery time and location). Using city logistics examples, I show how to embed disaggregate demand assumptions within routing problems. While doing so allows to better reflect the supply-demand interactions within the system, it also leads to hard optimization problems, for which suited solutions methods need to be designed.

■ FB-05

Friday, 10:30-11:30 - 11.10 Engelbert-Arnold-Hörsaal (EAS)

Semi-plenary talk Vredeveld

Stream: PC Stream
Semi-plenary session
Chair: *Guido Voigt*

1 - Additive approximation and approximation schemes for load balancing
Tjark Vredeveld

Many applications in discrete optimization lead to hard problems. Under common assumption, it is impossible to find an algorithm that (1) is efficient, (2) finds an optimal solution on (3) every instance. At least one of these requirements needs to be sacrificed to cope with these problems. In the area of approximation algorithms, the goal is to design algorithms that efficiently find provably good solutions. Typically, for approximation algorithms, provably good implies that we bound the approximation ratio of the value of the solution to the optimal value. One important reason for studying approximation algorithms is that often even on simplified problems, they give us insights in how to design heuristics for the real problem that needs to be solved. Furthermore, having a mathematical proof for an approximation guarantee often results in a deeper understanding of the structure of the underlying problem. Unfortunately, in some cases finding a guarantee on the approximation ratio is impossible, e.g., when the optimal solution value is 0. Or the approximation guarantee is overly pessimistic, e.g., Graham's (1966) seminal List Scheduling algorithm for makespan scheduling is guaranteed to find a solution with value at most twice the optimal value, but when processing times are small List Scheduling performs much better. To overcome these issues, we consider the concept of additive approximation algorithms. Instead of bounding the ratio, in additive approximation we bound the absolute difference between the value of the solution of the approximation algorithm and the optimal solution value. We apply the concept of additive approximation and additive approximation schemes, that can get arbitrarily close to an optimal solution, for several load balancing problems.

Friday, 12:00-13:30

■ FC-01

Friday, 12:00-13:30 - 30.95 Audimax A & B

Plenary talk Birge & Closing Event

Stream: PC Stream
Plenary session
Chair: *Alf Kimms*

1 - Lessons for OR from the COVID-19 Pandemic
John Birge

The COVID-19 pandemic has had a significant impact on all aspects of human society over the past two and a half years. In particular, researchers in many academic disciplines, including operations research, have devoted substantial effort to understanding various aspects of analyzing and controlling epidemics. These investigations have revealed new dimensions of the disciplines themselves as well as the underlying health phenomena. This talk will consider some of these lessons for operations research and its role in addressing issues for global policies.

Analytics and Learning

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Continuous and Global Optimization

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Discrete and Combinatorial Optimization

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Game Theory and Behavioral Management Science

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Heuristics, Metaheuristics and Matheuristics

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OR in Developing Countries

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Pricing and Revenue Management

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Project Management and Scheduling

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Simulation

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Software Applications and Modeling Systems

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Supply Chain Management

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Thursday, 15:45-16:30

Thursday, 16:30-17:15

Thursday, 17:30-19:00

Friday, 8:30-10:00

Friday, 10:30-11:30

Friday, 12:00-13:30