Wednesday, 9:00-10:20

■ WA-01

Wednesday, 9:00-10:20 - Bundeshaus

Opening session including plenary talk of GOR scientific award winner

Stream: PC Stream
Invited session

Wednesday, 10:40-12:00

■ WB-04

Wednesday, 10:40-12:00 - Eiger

Robust Discrete Optimization

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Marc Goerigk*

1 - Data-Driven Robust Optimization using Unsupervised Deep Learning
Jannis Kurtz, Marc Goerigk

Robust optimization has been established as a leading methodology to approach decision problems under uncertainty. To derive a robust optimization model, a central ingredient is to identify a suitable model for uncertainty, which is called the uncertainty set, containing all scenarios against which we wish to protect. An ongoing challenge in the recent literature is to derive uncertainty sets from given historical data.

In this talk we use an unsupervised deep learning method to construct non-convex uncertainty sets from data, which have a more complex structure than the typically considered sets. We show that the trained neural networks can be integrated into a robust optimization model by formulating the adversarial problem as a convex quadratic mixed-integer program. This allows us to derive robust solutions through an iterative scenario generation process. We compare this approach to a current state-of-the-art approach, which derives uncertainty sets by kernel-based support vector clustering. We find that uncertainty sets derived by the unsupervised deep learning method can give a better description of data and lead to robust solutions that considerably outperform the comparison method both with respect to objective value and feasibility.

2 - Benchmarking for Robust Discrete Optimization
Mohammad Khosravi, Marc Goerigk

Most robust combinatorial optimization problems are NP-hard and cannot be solved efficiently. Many algorithms have been developed for these challenging problems. But comparing them is difficult, as there is no benchmark set of problems available that every researcher could use. Instead, each experimental paper tends to recreate its own random instances to test algorithm performance.

While hardness analysis of problems considers carefully constructed instances that exhibit a specific structure which makes the optimization hard, this structure might not be present in random instances. In fact, many such randomly generated instances are often quite easy to solve and hinder the development of more advanced solution methods. The lack of benchmark problems means that solution methods have not seen as much improvement as one might expect.

In this presentation we show first steps to unblock this experimental cycle. We consider different optimization approaches to construct instances that are harder to solve than instances generated by uniformly random sampling. To this end, min-max (regret), two-stage and recoverable combinatorial problems with discrete, interval and budgeted uncertainty sets are considered. The idea is to change a given set of scenarios so that objective values of solution candidates become more balanced. This way, an optimization method such as branch and bound will need more iterations to prove optimality. Additionally, other random sampling methods are discussed to create hard instances. Benchmark sets will be made available by publishing them through a dedicated website, robust-optimization.com.

3 - Robust Combinatorial Optimization with Locally Budgeted Uncertainty
Stefan Lendl, Marc Goerigk

Budgeted uncertainty sets have been established as a major influence on uncertainty modeling for robust optimization problems. A drawback of such sets is that the budget constraint only restricts the global amount of cost increase that can be distributed by an adversary. Local restrictions, while being important for many applications, cannot be modeled this way.

We introduce a new variant of budgeted uncertainty sets, called locally budgeted uncertainty. In this setting, the uncertain parameters are partitioned, such that a classic budgeted uncertainty set applies to each part of the partition, called region.

In a theoretical analysis, we show that the robust counterpart of such problems for a constant number of regions remains solvable in polynomial time, if the underlying nominal problem can be solved in polynomial time as well. If the number of regions is unbounded, we show that the robust selection problem remains solvable in polynomial time, while also providing hardness results for other combinatorial problems.

In computational experiments using both random and real-world data, we show that using locally budgeted uncertainty sets can have considerable advantages over classic budgeted uncertainty sets.

4 - Gamma-Uncertainties for Robust Nonlinear Combinatorial Optimization
Dennis Adelhütte, Frauke Liers

Gamma-uncertainties have been introduced for adjusting the degree of conservatism in robust counterparts. It has mainly been applied to linear combinatorial optimization problems: Instead of aiming for solutions which are optimal regardless of how the uncertainties manifest, the objective is to ensure robustness against a discrete number of worst-case-realizations. We extend this approach from the mixed-integer linear to the mixed-integer non-linear case, with a focus on combinatorial optimization. By applying reformulation techniques that have been established for non-linear inequalities under uncertainty, we derive equivalent robust counterparts for non-concave and concave uncertainty. In both cases the computational tractability of the counterpart depends on the structure of the geometry of the uncertainty set. We resent robust counterparts for quadratic combinatorial optimization problems and present prototypical computational studies for the Gamma-robust Quadratic Assignment Problem to demonstrate the computational tractability in terms of solution quality and running time.

■ WB-05

Wednesday, 10:40-12:00 - Mönch

Software for OR - Solvers I

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Timo Berthold*
Chair: *Michael Bussieck*

1 - Recent developments in the FICO Xpress-Optimizer
Timo Berthold

We will present the latest news from the FICO Xpress linear, mixed-integer, and non-linear optimization solvers. This includes a brand-new heuristic emphasis mode for the MIP solver, a fully-fledged R-interface, and various improvements to nonlinear presolving. Of course, we will also present performance numbers.

2 - SAS Optimization: Recent Advances and Use Cases
Philipp Christophel, Imre Polik

In this talk the SAS Optimization solver development team reports on recent advances in areas such as presolve and simplex algorithms. It will also include recent use cases that highlight the versatility and flexibility of the SAS Optimization offerings.

3 - Introduction to the Cardinal Optimizer
Gerald Gamrath

In this talk, I will give a general introduction to the Cardinal Optimizer, or COPT, a relatively new optimization software. I will discuss the supported problem classes, different solving algorithms, and the modeling interfaces. The focus will be on the MIP solving capabilities added with the latest release of COPT.

4 - ODH|CPLEX - An Optimizer For Hard MIPs
Robert Ashford, Alkis Vazacopoulos

Mixed Integer Programming Models (MIPs) commonly solved are becoming larger and more complex in response to much more readily available data and cheaper computer resources. Computational effort often expands exponentially with model size and tools designed for optimizing smaller model instances may be of little use for the larger cases. ODH|CPLEX handles large models by co-running a set of heuristics within a traditional branch-and-cut optimizer so as to find good, usable solutions to problems that would otherwise be intractable. It also accelerates the optimization of large models which can be solved. We outline the structural decomposition technology used and demonstrate its effectiveness on many user instances as well as its ability to find solutions to standard test models to which no solution has been previously known.

■ WB-06

Wednesday, 10:40-12:00 - Jungfrau

Applications and Computational MIP

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Felix J. L. Willamowski*

1 - The student-project allocation problem as part of the timetabling in project-oriented schools
Michael Hölscher

The execution of timetabling in schools is a very complex planning task. Due to the high number of variables and constraints, the problem cannot be solved efficiently by hand in reality. Therefore, software support and methods from operations research are necessary to solve the problem. This paper will focus on project-oriented schools with an innovative learning concept, where teaching is no longer done in traditional classes but in small project groups that come together for a short period of time. The Universitätsschule Dresden, which is scientifically accompanied by the TU Dresden and where such a concept is applied and researched, serves as an application case. For the timetabling at such a school, the three sub-problems group formation, space planning and personnel planning can be identified. In this paper, the focus is on the first of these three: an optimal allocation of students to project groups, which can be referred to in the literature as the student-project allocation problem. For the problem, an integer linear programming model is formulated to maximize student satisfaction in the specific learning environment. Relevant aspects such as student preferences over projects, capacity and fairness are considered. Traditionally, such an assignment problem has to be solved once at the beginning of a planning period, for example when assigning students to courses at universities. Here, what is special is that students are part of multiple assignment processes because they work on numerous projects within a school year. Therefore, when considering the requirements, the individual problems should be regarded together. Using different instance sizes, the impact on computation time and feasibility is examined with the help of commercial solvers.

2 - Minimizing Airplane Boarding Time
Felix J. L. Willamowski, Andreas M. Tillmann

The time it takes passengers to board an airplane is known to influence the turn-around time of an aircraft and thus bears a significant cost-saving potential for airlines. Although minimizing boarding time therefore is the most important goal from an economic perspective, previous efforts to design efficient boarding strategies apparently never tackled this task directly. In this talk, we rigorously define the problem and prove its NP-hardness. While this generally justifies the development of inexact solution methods, we show that all commonly discussed boarding strategies may in fact give solutions that are far from optimal. We complement these theoretical findings by a simple time-aware boarding strategy with guaranteed approximation quality (under reasonable assumptions) as well as a local improvement heuristic and an exact mixed-integer programming (MIP) formulation. Our numerical experiments with simulation data show that for several airplane cabin layouts, provably high-quality or even optimal solutions can be obtained within reasonable time in practice by means of our MIP approach.

3 - Optimal location and configuration of tower cranes on construction sites
Thomas I. Maindl, Jannik Vogel

Choosing the right number, configuration, and locations of tower cranes can significantly impact the building schedule and reduce construction cost.

On construction sites, crane selection depends on many factors. These include the distance between the supply and demand points of each lift operation, the choice of material supply points, and the ground conditions on site. Typically, tower cranes come in different configurations regarding mast/hook heights, jib lengths, horizontal and vertical hook speeds, and boom rotation rate. For a certain crane configuration, load charts specify the maximum weight of the material that can be lifted at a certain boom radius. These need to be considered to determine feasible crane locations and configurations.

We present a MILP model implemented in GAMS that solves this decision problem minimizing the crane variable cost. It includes constraints that ensure the maximum weights of the material according to the load charts are not exceeded. In addition to the optimization model, a simple heuristic in closed form is presented.

For a real case of a construction site of mid-rise buildings, the resulting crane locations and configurations are discussed. Substantial benefits of applying the optimization model are found with a cost reduction of 22% compared to the worst case. While being much easier to apply, the heuristic still results in savings of about 9% compared to the worst case. While the optimization model is robust to an increase in the demand quantities, it requires disproportionately high computational resources for an increasing number of demand locations. The heuristic is found to deliver robust results with at most linearly growing runtimes when increasing both, the demand quantities and the number of demand locations.

4 - Exact Approaches for the Multi-Stop Station Location Problem
Erik Mühmer, Miriam Ganz, Marco Lübbecke, Felix J. L. Willamowski

The Multi-Stop Station Location Problem (MSLP) deals with the placement of stations in a provided network such that sequences of stops can be traversed with respect to range restrictions. Whenever a station is visited the remaining range is reset. The goal is to minimize the installation costs of the stations and the total travel costs. The MSLP is related to problems that arise in telecommunications or transportation, e.g., charging station placement problems. We present exact approaches based on mixed integer programming. On the one hand, we propose a compact MIP formulation that can be solved by standard MIP solvers. On the other hand, we consider reformulations of the problem that we solve using Branch-and-Price. Finally, we compare the presented approaches regarding their performance and possible drawbacks.

■ WB-07

Wednesday, 10:40-12:00 - Niesen

Planning in Supply Chain and Production Management I

Stream: Supply Chain and Production Management
Invited session
Chair: *Gerhard-Wilhelm Weber*

1 - Tactical planning of sugarcane harvesting and transport operations
Teresa Melo, Angelo Aliano Filho, Margarida Pato

We address in this talk a problem that involves the combined planning of harvest and transport operations for sugarcane over a multi-period planning horizon. The aim is to develop a tactical plan for the deployment of harvesting and transport equipment that establishes the periods for the execution of the harvesting operations on the sugarcane fields and specifies the type of harvesting machines and road haulage vehicles to be used. These decisions are made subject to multiple constraints related to the projected crop yield, the availability of machinery and road haulage vehicles, the expected demand for sugarcane at multiple mills, and further technical requirements specific to the harvesting operations. The problem includes two conflicting objectives, namely the minimization of the total cost incurred by the equipment used and the minimization of the total time required to harvest all the sugarcane fields. We propose a bi-objective mixed-integer non-linear programming model for this tactical planning problem and apply different linearization techniques to obtain a computationally tractable formulation. Pareto-optimal solutions are identified by the Progressive Bounded Constraint method that is extended to the problem at hand. A computational study is conducted on a set of semi-randomly generated instances that capture the characteristics of a Brazilian milling company. A comparative analysis highlights the trade-offs between economic performance and harvesting efficiency, thereby assisting the decision maker in making a more informed choice of the preferred tactical plan. Useful managerial insights are also provided into the profile of the harvesting and transport resources that should be used under different weather conditions and work schedules.

2 - Using K-means Algorithm in Sales Territory Design
Alper Döyen, Mehmet Kulu

Sales operations are one of the most important economic activities for companies. And the effective design of sales territories is an important managerial decision that has immense economic and social outcomes. Companies tend to define sales territories in order to increase their profits, maintain manageability of sales operations, assign fair workloads for the sales people and provide coverage on their clients. K-means as a clustering algorithm can be implemented to construct client subgroups which form sales territories. In this paper, for a real-world problem, we construct sales territories by using K-means algorithm. Performance of the K-means algorithm is evaluated by comparing its solution to the existing practice of the company and the mathematical model solution considering specified performance criteria.

3 - Data-Driven Decision Making for Strategic Production Planning in a Brewing Company
Markus Mickein, Matthes Koch, Knut Haase

Changing consumer behavior confronts the brewing industry constantly with new challenges and hence necessitates adaptation of the production system regarding changed requirements. Beer manufacturing is subject to restrictive dependencies, e.g., lead times, shelf life, multilevel product structures, and storage tank operations. Therefore, we propose a multilevel capacitated lot-sizing problem (MLCLSP) that considers brewery-specific constraints. The investigated brewing company produces 220 finished and 100 semifinished products on 13 production and 8 storage resources within 3 production levels. Since the MLCLSP is not solvable in a reasonable computing time for our problem instance, we apply a combination of the fix-and-relax heuristic to generate an initial solution and the fix-and-optimize heuristic to improve this solution. We present a computational study and managerial insights regarding changes in consumer demand, i.e., new products and changed production volumes. Our planning approach improves decision making in production management by revealing the impact of consumer behavior on the entire production system. It provides a good solution quality within a few minutes and realizes cost savings while reducing manual planning effort.

4 - Sustainable Aggregate Production Planning with Overtime, Outsourcing and Human Factors under Uncertain Seasonal Demand
Gerhard-Wilhelm Weber, Selma Gütmen, Erfan Babaee Tirkolaee, Alireza Goli

Aggregate production planning (APP) is a medium-range production and employment planning that deals with the main challenges of manufacturing industries, such as production and outsourcing quantities, hiring and lay-off rates and inventory levels. On the other hand, sustainable development plays a key role in the problem based on global issues, particularly in environmental aspects. This study develops a novel multi-objective mixed-integer linear programming (MILP) model to formulate the sustainable APP problem with overtime and outsourcing options under interval-valued or fuzzy seasonal demand. The objectives are to concurrently minimize total cost of the production system, minimize total environmental pollution and maximize customers' satisfaction level. To deal with the multi-objectiveness of the model, the augmented epsilon-constraint technique is implemented. A numerical example is then investigated to test the performance and validity of the proposed mathematical model. Finally, the behavior of the objective functions is evaluated against the fluctuations of key parameters based on unstable real-world situation and managerial insights and decision aids are suggested. The particular novelty of our study is the rich involvement into our APP of Human Factors and additional goals of Workforce Satisfaction.

■ WB-08

Wednesday, 10:40-12:00 - Stockhorn

Optimal planning and operation of low-carbon distributed energy systems

Stream: Energy and Environment
Invited session
Chair: *Giovanni Sansavini*

1 - Robust optimization of multi-energy systems with seasonal storage and yearly constraints

Alessandro Francesco Castelli, Luca Moretti, Giampaolo Manzolini, Emanuele Martelli

Several optimization approaches have been proposed for short-term operation of Multi Energy Systems (MESs) while very little attention has been paid to long-term operation of MESs with seasonal storage and/or units with yearly-basis constraints. In such cases both short- and long-term uncertainty must be considered in the problem. This work proposes an approach for the robust operational optimization of a MES on the three key time scales: seasonal, day-ahead and real time hourly operation. The approach consists in a rolling horizon algorithm based on an Affine Adjustable Robust Optimization model for optimizing both day ahead schedule (commitment and economic dispatch) and the decision rules to adjust the real-time operation. Input of the robust optimization model are (i) the day-ahead forecasts of renewable production and energy demands with their corresponding uncertainty set, (ii) past and future expected performance of the units subject to yearly constraints, and (iii) target end-of-the-day charge levels for the seasonal storage system. Both long-term expected performance and storage state-of-charge trajectory are estimated by optimizing the operation over representative years defined on the basis of the past measured data using a MILP formulation. The variability of the input profiles across different years is taken into account as well. Computational tests are performed on two real-world case studies across the whole year. Results showed show that the optimized operational schedule is only 2-6% higher than the ideal solution which corresponds to the minimum possible operational cost.

2 - A novel temporal approach for efficient and accurate MILP models of energy systems

Matteo Gazzani, Lukas Weimann

Achieving the 2050 emission reduction goals requires radical changes in the energy system. Any realistic pathway to curb climate change needs coupling and integration of the whole energy system. Accordingly, accurate, cross-sectorial models of the energy system are essential. To support complex decisions such as the system design and operation, models need to fully explore the exponentially-sized set of possible solutions while guaranteeing optimality of the outcome. This leads to inherently complex optimization problems, whose size is often intractable on regular computers. As a result, and although the speed of computers and solvers has significantly increased in the last decades, energy system models have been kept over-simplified. The level of accuracy unfolds along the physical dimension - the extent to which the system components represent real behavior - the time dimension - decisions every minute/hour along a (multi)year time horizon - and the space dimension - the locations of components in the network. The three are intertwined and define the final model accuracy. With this contribution, we will discuss how the computation time of accurate optimization models can be reduced via a new time-hierarchical solution method. The fundamental approach is to create a problem formulation where the time-resolution increases with every hierarchy layer. Progressing through the layers, constraints are implemented and adjusted to reduce the design space, keeping the computing time low. The new method is a substantial improvement over the use of design days. We will quantify this by comparing with a full time resolution (i.e. no time simplification) and with design days. To this end, we will present a number of case studies, including national and local energy systems.

3 - Uncertainty analysis for optimal design and assessment of active electricity distribution networks

Annalisa Guidolin, Raphael Wu, Paolo Gabrielli, Giovanni Sansavini

Transitioning to sustainable, reliable and affordable energy is a worldwide challenge subject to many uncertainties. This project characterizes and quantifies the uncertainty associated with the design of active electricity distribution networks (ADNs) and microgrids with islanding ability. Here, distributed energy resources (DERs) are optimally placed to minimize total annual costs while achieving reliability and greenhouse gas emission targets. To understand which geographical, techno-economic and regulatory circumstances are amenable to DER and microgrid installation, the model response to the variation of 48 input parameters is tested. First, the uncertainty of the renewable energy sources and load profiles is characterized through the definition of "energy regions" based on climate Köppen-Geiger classes, as well as wind and solar potential. Then, the optimal number of regions to capture most of the global variability is defined via the analysis of various clustering algorithms. For each region, a sensitivity analysis is performed through the elementary effect method, which enables to rank the parameters by relevance, and shows the variability of optimal ADN design throughout the regions. The elementary effects of all inputs, outputs and regions are aggregated with a new sensitivity measure and used to determine a subset of highly influencing parameters. Furthermore, the most influencing parameters are tested through an uncertainty analysis with distributions based on extensive literature research. Monte Carlo Filtering is finally used to capture the combinations of parameters that lead to a cost-competitive installation of DERs and microgrids.

4 - Optimal trading of flexible power consumption on the day-ahead market

Neele Leithäuser, Till Heller, Elisabeth Finhold

As power generators shift from inert power plants to more volatile renewable sources of electricity, consumers with a high, uniform base load become less attractive for the energy market. In contrast, variable loads allow energy-intensive businesses to monetize this flexibility in the electricity market. In the aluminum industry, engineering innovations have enabled such flexibility. A virtual battery can balance changing power inflows over a period of a few days. We have modelled the optimization problem of when and how to use this flexibility on the day-ahead energy market based on hourly price forecasts as a linear program. Beyond the expected revenue, we also consider technical costs incurred in an unsteady energy schedule in a multi-objective fashion. The price level of the next week influences the optimality of the next day's buying and selling decisions. We hence solve the optimization problem for a longer period. However, on the day-ahead market, we have to fix only the bids for one day. The decisions of later days can still be revised in subsequent auctions, when updated price prognoses are available. Therefore, we embed the optimization problem in a rolling horizon planning framework. In our talk, we generalize the specific planning problem to a broader range of applications and analyze the main influences on a profitable trading strategy.

■ WB-09

Wednesday, 10:40-12:00 - Gantrisch

Drone and Robot Delivery

Stream: Logistics and Freight Transportation
Invited session
Chair: *Alexander Rave*

1 - A Branch-and-Price Algorithm for a Delivery Network with Parcel Robots

Nicklas Klein, Stefan Schaudt, Uwe Clausen

The logistics industry has been facing growing transport volumes combined with increasing customer expectations in recent years. To overcome these challenges, new innovative delivery concepts have been developed. One concept for last-mile deliveries in urban environments is based on small electrical robots that drive autonomously on sidewalks and pedestrian zones. These vehicles can deliver goods of daily use such as groceries, parcels, medicine, or meals.

This study examines a delivery network with autonomous robots. The delivery network consists of a fleet of single unit capacity vehicles, a set of depots equipped with recharging stations and a set of customers. Each customer is associated with an individual time window and a profit that can be collected when served. Due to the single unit capacity of the vehicles, a depot visit is required between each pair of customers, which is a difference to classical routing problems. The goal of this problem is to find vehicle routes such that the sum of collected profits is maximized. The problem is solved with an exact branch-and-price algorithm. The pricing problem contains not only the generation of customer sequences, but also the decision on intermediate depot visits and recharging times. Computational studies on benchmark instances show promising results.

2 - Sequence and Speed Optimization for Delivery Robots

Stefan Schaudt, Tolga Bektas

The growth rate in Courier Express Parcel markets presents a major challenge for the logistics industry worldwide. Innovative approaches and solutions are needed. For densely populated areas, so-called delivery robots are a promising alternative to traditional trucking. Delivery robots represent a rather new technology, capable of transporting one good at a time autonomously on sidewalks. These robots drive at walking speed and are equipped with the same technology used for autonomous driving. The advantage of a robot delivery is that the delivery can commence upon receiving a request, which helps to enhance customer satisfaction. In this study, we assume that the driving speed of the robots is controllable and can be optimized, in order to minimize the energy needed. This gives rise to a joint sequencing and speed optimization problem to serve a given set of customers within pre-specified time intervals, by using a fleet of robots. The energy consumption is considered as a quadratic function in speed. To solve the stated problem a branch-and-price approach is presented, where the arising pricing problem is solved with a resource constraint elementary shortest path problem (RCESPP). Within the RCESPP the optimal speed on each leg of a given tour can be calculated with a polynomial time algorithm.

Tests were carried out with the branch-and-price algorithm and compared to existing results for a similar problem class. The comparison shows that our approach outperforms the existing results and is capable of solving instances with up to 50 nodes.

3 - Drones for Relief Logistics under Demand Uncertainty

Okan Dukkanci, Achim Koberstein, Bahar Yetis Kara

This study presents a humanitarian delivery problem, where critical relief items are distributed to the disaster victims gathered at assembly points after a disaster in particular an earthquake. Since roads may be blocked by possible debris after an earthquake, drones will be used as a primary transportation mode. As the exact time and the magnitude of an earthquake cannot be predicted, it is a highly stochastic event. Therefore, the demand uncertainty is considered and the objective is to minimize the total unsatisfied demand subject to a time bound constraint on deliveries and range and capacity limitations of drones. A two-stage stochastic programming formulation and its deterministic equivalent problem formulation are presented. As an exact solution approach, the scenario decomposition algorithm is implemented. To apply this study to a real-life application, a case study is conducted based on western (European) side of Istanbul, Turkey. One of the main reasons is to choose Istanbul is that geological studies and surveys indicate in a near future, a major earthquake is expected to happen in Istanbul. The talk will present computational results on the performance of the scenario decomposition algorithm, value of stochasticity and expected value of perfect information under different parametric settings.

4 - Vehicle Fleet Planning for Parcel Delivery with Trucks and Aerial Drones

Alexander Rave, Pirmin Fontaine, Heinrich Kuhn

In the context of parcel delivery, aerial drones have great potential that comes especially true in rural areas. In these areas drones can fly autonomously and operate faster than conventional delivery trucks particularly when certain obstacles, e.g., mountains, rivers, lakes etc. must be overcome. A delivery fleet consisting of trucks can be extended by drones in two ways: Drones and trucks might conjointly serve customers, if drones are launched from trucks, or independent of each other, if drones are launched from microdepots or the central distribution center (CDC). For an optimal use of drones in last-mile delivery within a tactical planning horizon, it is necessary to determine the optimal fleet mix of trucks and drones.

We develop a multi-level decision support model that decides on the optimal integration of aerial drones in a current vehicle fleet with trucks of a CEP (courier, express, and parcel) service provider that minimizes total costs while fulfilling a certain service level. The problem setting is modeled as a mixed-integer linear program (MILP). The MILP model allows to assess the benefits of different transport concepts as well as the impact of mixing different delivery modes. We develop a specialized heuristic procedure that bases on the adaptive large neighborhood search (ALNS) to solve practice-relevant instances.

We present a case study for parcel delivery in a rural area where customers are residing in small villages. Taking both variable delivery and fixed investment costs into account, the use of arial drones, if either launched from trucks or launched from micro depots or the CDC always leads to cost advantages compared to truck delivery. If delivery methods are mixed, additional delivery cost savings of up to 5% can be achieved.

■ WB-10

Wednesday, 10:40-12:00 - Schreckhorn

Transportation and mobility planning

Stream: Logistics and Freight Transportation
Invited session
Chair: *Lorena Reyes-Rubiano*

1 - Measuring the effects of disruptions in city logistics: Managerial insights from a large city perspective

Lorena Reyes-Rubiano, Elyn Lizeth Solano Charris, Andrés Muñoz-Villamizar

The transport logistics patterns and the structure of the cities are essential for the functioning of a society and economy. The phenomenon of globalization and new market patterns has generated an increase in demand for the transportation of products and services. As a result, transportation logistics in cities are more challenging. Furthermore, transportation is sensitive to disruptions due to system failures and climate changes that hinder city logistics. This work is focused on measuring the impact of disruptions in a highly congested city. An extensive number of experiments are presented to evaluate the effects of multiple disruptions on the transportation network. This work considers realistic data on travel times, delivery frequency, and customer locations for Istanbul. We measure the impact of disruptions on routing decisions using the Google application programming interface (API) to determine routing decisions. The impact is measured in terms of travel time. Our results provide managerial insights for decision-makers to assess and design policies that make the transportation system more robust.

2 - Revenue Maximizing Tariff Zone Planning for Public Transport Service Providers

Lorena Reyes-Rubiano, Sven Müller, Knut Haase

This paper presents the tariff zone planning problem, which pursues objectives such as maximizing ridership and revenue for public service providers. We propose an optimization approach basis on partitioning the service area into zones and find a price per zone such that the total expected revenue is maximized. It is assumed that the price per zone takes a discrete set of values, the number of public transport trips depends on the price system, public transport passengers always choose the time-shortest path. We perform a series of numerical experiments with artificial instances of size 36, 81 and 121 zones (nodes). We optimally solve each of the instances using GAMS/CPLEX. The results demonstrate that expected revenue can be maximized without decreasing transit ridership. Also, this paper sheds light to urban public service providers on how to enforce contiguous tariff zones to maximize the expected total revenue.

3 - A data-driven response to dynamic spatio-temporal transportation requests

Sacha Varone, Anthony Tomat

We consider a decision problem in a transportation company.

Every day, the company receives transportation requests by phone from different customers. A request consists of an origin, a destination, and a time window within which the request must be fulfilled. The decision to accept or reject the request has to be made within a short period of time: between seconds and minutes.

We develop an analytical decision process to accept or reject a request based on the expected revenue. Since this is real data with GPS coordinates, we use a geographic information system to calculate transportation times and lengths. We use historical company data to predict new spatio-temporal requests, using clustering and probability methods. Then, a simulation generates instances of vehicle routing problems. These are solved using heuristics from open-source tools, allowing for hypothetical revenues. The request can finally be accepted either if the expected value added of the request is positive, or because it increases the company's revenue compared to the known situation at the time the request is expressed.

We test our methods on real data, as well as on generated data.

4 - Monte Carlo Simulation for Route Planning under Uncertainty: Case Study and Proof of Concept

Jan Gertheiss, Florian Jaehn

We consider the problem of choosing a route from a start point S to a target T from a relatively small set of options. We assume that travel times are not deterministic but subject to some stochastic mechanism/uncertainty. For modeling and analyzing travel times, we use Monte Carlo simulation based on mixtures of gamma distributions and soft thresholding. Instead of focusing on mean travel times, we discuss multiple criteria for decision making. Our approach is illustrated by an example from public transportation: traveling from Göttingen to Cologne by ICE train of Deutsche Bahn (DB). Taking the perspective of an individual passenger, we can basically choose between two options: A, via Hanover (Central Station), or B, via Frankfurt (Central Station and/or Airport). For instance, our results (i) indicate that option B (which is more expensive and typically shown by the DB app) decreases both mean travel time and the risk of missing a (pretended) appointment at Cologne, compared to option A. On the other hand, however, (ii) actual travel times may vary substantially within options, and it is by no means clear that B is faster than A for a concrete trip. In addition, (iii) it can be advantageous to choose a train that is not shown by the DB app at all (i.e., without "expert knowledge" which settings to change). Finally, we discuss ways (such as generalized additive models for location, scale and shape/GAMLSS) how to infer model parameters from historic data and update the model, and hence decision rules, using real time data.

■ WB-11

Wednesday, 10:40-12:00 - Wildstrubel

Financial Modelling I

Stream: Finance
Invited session
Chair: *Volker Seiler*

1 - Mini flash crashes in Austria: An empirical study

Viktoria Steffen

Financial market crashes have been present for over fifty years but the speed and frequency has increased from slow motion crashes lasting several days to mini flash crashes unravelling in a second or less. Mini flash crashes have been studied for several large financial markets such as the U.S. (e.g. Golub et. al. (2012), Braun et. al. (2018)), the United Kingdom (Aquilina et. al. (2018)) as well as France (Bellia et. al. (2018)). As high frequency data on both trades and the order book is needed, small developed markets have not been studied yet. We study mini flash crashes on the Austrian capital market from January 2005 until March 2018, which is the longest investigation period so far. Following Nanex Inc., a stock is identified as having a mini flash crash if the stock is ticking down (up) at least ten times before ticking up (down) within a duration of 1.5 seconds and a minimum price change of 0.8%. We find 142 mini flash crashes according to this definition. Extending the definition to a duration of 10 seconds and a minimum price change of 0.5%, we detect a total of 579 mini flash crashes. We find that down crashes occur more frequently, as more than 60% of our sample consists of down crashes. Also, most crashes recover within one trade. More than 15% of the detected mini flash crashes have a duration of less than one second. The number of both up and down crashes peaks in 2017. In line with Braun et. al. (2018) we find that most crashes can be attributed to companies from the financial sector with an average of 10.5 down crashes and the highest standard deviation. One company from the financial sector has four down crashes within the same day.

2 - China-to-FOB Price Transmission in the Rare Earth Elements Market and the End of Chinese Export Restrictions

Volker Seiler

This paper investigates the impact of the end of the export quota system (EQS) on China-to-export price transmission in the rare earth elements market, taking into account threshold effects and price transmission asymmetries. The results indicate that export prices became more responsive to changes of Chinese prices after the Chinese Ministry of Commerce (MOFCOM) abandoned the exort quota policy. While price shocks wash out much quicker in the Post-EQS period, we do not find evidence for rockets and feathers-type of behaviour.

3 - Social Trading: Do Signal Providers Trigger Gambling?

Andreas Oehler, Julian Schneider

Social trading - also referred to as copy trading - is an interactive platform-based innovation facilitating visibility and traceability of signal provider trading activities. Based on published portfolio transaction and return track records, platform users can copy one or several signal providers, i.e. delegate their investment decisions, and thereby become signal followers. Allowing signal providers to administer purely virtual portfolios, in combination with a renumeration scheme based on performance fees and high watermarks, creates convex or option-like incentives (Carpenter, 2000; Doering and Jonen, 2018). We argue that the incentive structure imposed by social trading providers, including a very limited monetary downside risk for signal providers, may motivate traders to gamble. In this context, we assess the factors that have an impact on signal provider lottery-like stock transactions (Kumar, 2009; Bali et al., 2011). We provide empirical evidence that signal providers tend to increase the traded relative share of lottery-like stocks when being located at an extreme end of the relative performance spectrum. Furthermore, we provide evidence that underperforming signal providers increase their net exposure towards lottery-like stocks, in turn exposing signal followers to a lottery-like return structure - triggering gambling.

■ WB-12

Wednesday, 10:40-12:00 - Faulhorn

Line Planning and Vehicle Scheduling in Public Transport

Stream: Mobility and Traffic
Invited session
Chair: *Stefan Frank*

1 - Optimal Line Plans in the Parametric City and the Impact of In-Motion Costs

Berenike Masing, Niels Lindner, Ralf Borndörfer

Line Planning in public transport involves determining vehicle routes and assigning frequencies of service such that travel demands are satisfied. The goal is to provide the least cost intensive line plan for the operator, yet achieve high customer satisfaction. We compare two objective functions, which include both operator and user costs: The first considers only in-motion costs (IMC), which are computed as a weighted sum of linear travel times for operators and users, respectively. The second, the Value of the Resources Consumed (VRC) is a socio-economically driven cost function, which, apart from in-motion times, takes into account delay caused by boarding and alighting, waiting times, and transfer penalties. We perform an analysis on the "Parametric City", a generic, flexible model developed by Fielbaum et al. to represent a large range of cities for the purpose of line planning. In the past, Fielbaum et al. considered a similar problem: They compared the VRC of symmetric line structures that were obtained by heuristic means. We propose to instead solve the line planning problem (LPP) with IMC as objective. We formulate LPP as a mixed integer linear program, which includes free passenger routing, considers an extended line pool – all bidirectional paths and directed cycles in a graph are line candidates – and allows asymmetric solutions. Based on the solutions of LPP, we analyze their performance with respect to both IMC and VRC. Despite their fundamentally different setup, the two objectives turn out to be qualitatively comparable.

2 - Benders Decomposition for the Periodic Event Scheduling Problem

Niels Lindner, Rolf Van Lieshout

The Periodic Event Scheduling Problem (PESP) is the central mathematical model behind the optimization of periodic timetables in public transport. A variety of formulations as mixed integer linear programs (MIP) are at hand, but solving even medium-sized PESP instances to optimality is computationally out of reach for state-of-the-art commercial MIP solvers.

We apply Benders decomposition to the incidence-based MIP formulation of PESP. This results in a novel MIP formulation for PESP, which is some sense dual, as an optimal solution to any restricted master problem yields a lower bound for the optimal PESP objective value. It turns out that the Benders decomposition exhibits particularly nice features: The Benders subproblem is a minimum cost network flow problem. Moreover, the feasibility cuts are equivalent to Odijk's cycle inequalities, which are well-known in the context of periodic timetabling. The optimality cuts belong however to a new family of cutting planes, based on spanning trees and not on cycles, in contrast to many types of known inequalities for PESP.

On the computational side, we integrate the Benders approach into a branch-and-cut framework using the MIP solver CPLEX. We assess the performance of this method on instances of the benchmarking library PESPlib, and compare primal and dual bounds with the ones obtained from conventional MIP formulations.

3 - Delay Management with Integrated Vehicle Scheduling

Vera Grafe, Alexander Schiewe, Anita Schöbel

The task of delay management in public transport is to decide whether a vehicle should wait for a delayed vehicle in order to maintain the connection for transferring passengers. In classic delay management, the vehicle schedules are ignored, although they have an influence on the propagation of the delay through the network. Hence, in this paper we consider different ways to incorporate vehicle scheduling in the delay management stage of public transport planning. Since the IP formulation for the integrated problem is hard so solve, we investigate bounds to IP formulations that are easier to solve and develop several heuristics for the integrated problem. Our experiments on close-to world instances show that integrating delay management and vehicle scheduling may reduce the overall delay by up to 39 percent. We also compare the runtimes and objective function values of the different heuristics. We conclude that we can find competitive solutions in a reasonable amount of time.

4 - A genetic algorithm solving the integrated timetabling and vehicle scheduling problem

Lucas Mertens, Bastian Amberg, Natalia Kliewer

While operational transport planning problems are historically solved sequentially, steadily evolving solution approaches and continuously developing IT-Hardware lead to new possibilities for integrated solving planning-related decision problems in a reasonable time. In our study, we focus on the first two steps of operational public transport planning: the timetabling (TT) and vehicle scheduling problem (VSP). Given a network design and a completed line planning, the priority within constructing the timetable aims at achieving a high range of service, while keeping the total anticipated costs reasonable. Given a timetable the VSP is concerned with allocating service trips to specific vehicles optimally. Historically, the TT is computed first and serves as an Input for the VSP. However, integrated optimizing both planning steps can lead to an improved overall solution regarding a variety of objectives. Given real-world problems, however, the computational time for exactly solving the integrated problem might not justify the solution quality gap compared to a heuristic solution approach. In this paper, we develop a genetic algorithm (GA) solving the TT and VSP integrated based on a Time-Space network and compare the results regarding the solution quality and runtime with an exact solution approach. Comparing either result for small and medium-sized instances, the optimality gap for solutions obtained by the GA is insignificant in most executions. Aiming to achieve good solutions in a reasonable time, the developed heuristic fulfills each practical requirement while resulting in small quality gaps compared to exact solutions only.

■ WB-13

Wednesday, 10:40-12:00 - Blüemlisalp

Revenue Management for Logistics and Mobility

Stream: Revenue Management

Invited session

Chair: *Robert Klein*

Chair: *Claudius Steinhardt*

1 - Feeding the Nation - E-Groceries in Times of Crisis

Jonas Schwamberger, Moritz Fleischmann, Arne Karsten Strauss

At the outbreak of the Corona pandemic, demand for online grocery orders for both Click & Collect and attended home delivery by far outstripped supply. In the UK, the booking system of some retailers could not even handle the flood of incoming requests, forcing retailers to instead proactively reach out to certain priority customer segments with the aim of serving as many high priority customers as possible. In this paper, we investigate how to best manage demand in this new environment, and we give an outlook on how these techniques can be valuable after the pandemic as well.

2 - On the properties of opportunity cost in dynamic demand management and vehicle routing problems

Vienna Klein, David Fleckenstein, Claudius Steinhardt, Robert Klein

Demand control problems in the field of vehicle routing are characterized by a stream of customers arriving dynamically over a booking horizon and requesting logistical services which are fulfilled by a given fleet of vehicles. Customers commonly have heterogeneous preferences for different fulfillment options. Hence, demand management methods can be applied to control the booking process with the aim of maximizing total profit. The quality of demand management decisions depends to a large extent on an accurate estimation of opportunity cost. In the context of integrated demand management and vehicle routing, this term denotes the monetary value of the fulfillment resources that are expended as a consequence of selling a certain logistical service to an arriving customer. As the concept of opportunity cost is such an essential component of any demand management approach, we formalize its definition specifically for vehicle routing applications. Drawing on a prototypical model, we investigate and illustrate properties of opportunity cost in dynamic models. Finally, we discuss implications for approximate dynamic programming approaches which are proposed in the recent academic literature on various problem settings.

3 - Policy-Based Dynamic Pricing in Shared Mobility Systems

Matthias Soppert, Claudius Steinhardt

Shared mobility systems have become a wide-spread alternative within the inner-city mobility landscape. Modern systems offer one-way trips, which yield high flexibility to the customer but also cause imbalances between supply and demand that need to be rebalanced for profitable operation. Pricing has turned out to be a promising means. We consider the on-line problem of a shared mobility system provider to simultaneously set discrete minute prices for all zones of the operating area. The action space of the considered stochastic dynamic decision problem grows exponentially with the number of zones, such that value-based approaches do not scale. Instead, we propose a problem-specific policy-based approach, adapted from the realm of deep reinforcement learning, which can handle the large actions space. Preliminary results indicate that our approach surpasses the optimal static pricing as well as dynamic benchmarks.

4 - Customer-centric Dynamic Pricing in Shared Mobility Systems

Christian Müller, Jochen Gönsch, Matthias Soppert, Claudius Steinhardt

A free-floating carsharing system offers customers the flexibility to pick up and drop off an available vehicle at any location within the provider's business area. This flexibility has the drawback of often occurring distribution imbalances of vehicles within the network. There are two different strategies to counter this imbalance. The first one is realized by the provider through manual relocation and the second is carried out by the customers by providing monetary incentives for certain vehicles dependent on the number of available vehicles in vicinity. We developed a dynamic pricing approach for the second strategy based on dynamic programming to maximize profit. Due to the curse of dimensionality, we use a dynamic programming approach, which approximates the expected future revenue by considering the historical profit of vehicles in the near vicinity.

■ WB-14

Wednesday, 10:40-12:00 - Wetterhorn

Forecasting

Stream: Analytics
Invited session
Chair: *Ralph Grothmann*
Chair: *Sven F. Crone*

1 - Using neural networks to forecast parcel quantities in a distribution network

Gabor Tamas, Elisabeth Zehendner, Christian Paier, Emel Arikan, Gerald Reiner

The developments of neural networks have heavily influenced the field of forecasting. Several neural network-based forecasting models have been invented, which are by nature suitable to be used as global forecasting models. As the number of time series in a dataset increases, globally trainable models become favorable since they can use the information embodied in the historical dataset more effectively. Additionally, global forecasting models are shown to work well in fast-changing business environments in which relevant time series tend to have a relatively short length.

In the presented research, a neural network-based forecasting approach is developed to predict parcel quantities in a parcel distribution network. The Pytorch Forecasting package is used for the implementation and comparison of different neural network architectures. The comparative evaluation is carried out using real-world data from a major logistics and postal services provider.

2 - Forecasting Customer Demand with Deep Neural Networks

Ralph Grothmann, Ulrike Dowie

The case presented illustrates the application of deep neural networks on forecasting customer demand. Accurate forecasts are crucial for successfully managing the supply chain. During the production process, material and capacities need to be planned in accordance with the expected demand to ensure delivery capability and reliability. By applying deep forward neural networks, demand patterns can be identified in the sales time series of more than 1.000 products in the area of industrial controls. The models use autoregressive as well as seasonal components. Additionally, macroeconomic factors are included to explain the demand fluctuations. The approach incorporates an automated model building, training and evaluation scheme, all of which are implemented in a scalable cloud solution. The forecasts are combined with uncertainty measures to derive decision support for our demand planning department.

3 - Using Internet-of-Things Data at the Point-of-Consumption for Demand Forecasting and Inventory Management: The Case of Professional Coffee Machines

Sandria Weisshuhn, Yale T. Herer, Kai Hoberg

Internet-of-Things-enabled systems that monitor inventories and sales are the next technological advancement in demand forecasting and replenishment. Unlike traditional systems that record purchases via cash registers or RFID technology at the point-of-sale, these novel systems can track product usage via smart, connected devices at the point-of-consumption, i.e., directly at the end user. This usage data promises to be a valuable basis for automated ordering and replenishment processes. We study such a system in the context of professional coffee machines and collaborate with a large manufacturer/retailer in the coffee industry. Our dataset contains information on more than 83 million drinks served since 2018 for nearly 6,500 customer-machine combinations. Complexities in this context pertain to unique usage patterns in different customer segments (such as office kitchens, gastronomy, and gas stations), different customer behavior in managing machine supplies, and the integration of multiple machine types into a common system. We approach these challenges by estimating segment-specific models for demand forecasting and customer-specific models for inventory management. In addition, we incorporate human and technology-based inventory record errors into our inventory models. Overall, we seek to develop tools for managing smart replenishment systems in practice. Our findings extend to consumer contexts and suggest important implications for both stationary and online retail.

4 - Dynamic data collection in production and logistics

Benedikt Finnah, Jochen Gönsch, Alena Otto

The collection and maintenance of relevant data is the cornerstone for automation and streamlining of logistics and transportation; it is also the cornerstone for the digitization at companies, in general. However, many logistics and production companies do not possess all the data they need, or the available data is of insufficient quality. As a consequence, much potential for better decision making and introduction of new technologies remains untapped. Overall, data collection and maintenance usually require significant lump-sum investment and high running cost. Especially if the data should be known exactly, exhaustively and with certainty. An example of such data is the data on the required precedence relations between tasks. A state-of-the-art procedure to collect the data on precedence relations is interviews with experts. Interviews refine the uncertain and incomplete data collected or derived from other sources, such as sensors. Each interview question takes about 3-4 minutes or more. Because (automated) decision making in some logistics and production problems involves about 3.000 tasks, or about 4.5 million task pairs, it is obvious that the collection of complete information is impossible. Therefore, we study the data collection problem as an optimization problem. For a given number of questions, we determine which questions to ask to optimize the business results. To solve this problem, we use approximate dynamic programming.

■ WB-15

Wednesday, 10:40-12:00 - Silberhorn

GOR PhD thesis awards 2021

Stream: PC Stream
Sponsored session
Chair: *Peter Letmathe*

1 - Rebalancing in Shared Mobility Systems - Competition, Feature-Based Mode Selection and Technology Choice

Layla Martin

Vehicle sharing services commonly face the problem of unbalanced demand: The number of vehicles rented from a location may not equal the number of vehicles returned to this location. To counteract demand imbalances, operators rebalance their fleet, i.e. move vehicles from locations with an excess supply to locations with an excess demand. We investigate three extensions of the rebalancing problem: competition, modal selection, and driverless vehicles. With increasing competition, operators must consider where other operators currently have vehicles, as well as how they rebalance their fleets. We present a model that considers competition in rebalancing. In Munich, operators can gain up to 40% of their profit due to considering competition. However, operators in Munich lose up to 12% of their profit due to the presence of competition (compared to a merger). Vehicles can be rebalanced by loading them onto a truck, or by driving them. In the latter case, staff must be rebalanced too, i.e., workers have to give each other lifts, bike or use public transit to reach the next vehicle. We study which features drive the choice for either of the modes using classifiers based on multiple linear regression, multinomial logistic regression, and decision trees. With this novel approach, we show that the modal choice is mainly driven by wages for workers, and vehicle costs. The advent of driverless vehicles will directly impact the shared mobility market, as operators consider whether to procure driverless vehicles. We study the technology choice and mix problem operators face, balancing investment costs with operational costs and contribution margins. In a case study using data from Chinese ride-hailing provider DiDi, operators often benefit of mixed fleets if direct costs are equal.

2 - Scheduling and Packing Under Uncertainty
Franziska Eberle

Incomplete information is a major challenge when translating combinatorial optimization results to recommendations for real-world applications since problem-relevant parameters change frequently or are not known in advance. A particular solution may perform well on some specific input data or estimation thereof, but once the data is slightly perturbed or new tasks need to be performed, the solution may become arbitrarily bad or even infeasible. Thus, we would like to design algorithms that deal with incomplete information while performing sufficiently well. We explore scheduling and packing, two fundamental fields of combinatorial optimization, under two models of uncertainty: online and dynamic. More precisely, we focus on online throughput maximization and dynamic knapsack. For online throughput maximization with and without commitment, where jobs arrive online over time and the scheduler wants to maximize the total number of jobs completed before their deadlines, our algorithms achieve provable worst-case guarantees, which match our lower bounds. For the multiple knapsack problem, where items and knapsacks arrive and depart dynamically while the goal is to efficiently recompute a solution, our algorithm is the first dynamic algorithm with poly-logarithmic update time, and it finds near optimal solutions.

3 - Operations Management in the Sharing Economy
Moritz Behrend

The sharing economy subsumes various concepts in which members of a community provide services to each other. Two of these concepts are item-sharing and crowdshipping. In item-sharing, members grant others a temporary access to the items they own, such as tools or leisure equipment. In crowdshipping, private drivers conduct delivery jobs for other people on trips they would make anyway. These two concepts are so far dealt with on separate platforms that operate in isolation. However, they could complement each other well when the available transportation capacity in crowdshipping is utilized to support the cumbersome peer-to-peer item exchanges in item-sharing. The scope of this talk is to investigate potential benefits of integrating item-sharing and crowdshipping on a single platform. To this end, we address the operations management of such a platform, we present optimization models and methods for the corresponding decision making, and we derive managerial insights from numerous computational experiments. The results confirm that the two concepts are mutually beneficial and that a well-designed operations management allows to effectively serve demands announced on such a platform. It is also demonstrated that a shared use of items can lower the environmental impact of consumption.

4 - Approximation Schemes for Machine Scheduling
Marten Maack

In the classical problem of makespan minimization on identical parallel machines, or machine scheduling for short, a set of jobs has to be assigned to a set of machines. Each job has a processing time and the goal is to minimize the maximum machine load. It is well known that this problem is NP-hard, but admits a polynomial time approximation scheme (PTAS). For many natural variants of the problem, however, the approximability status is less clear. The presented dissertation investigates several of these variants. One of the corresponding results is presented in more detail: Integer linear programs of configurations, or configuration IPs, are a classical tool in the design of algorithms for scheduling and packing problems. For instance, they can be used to obtain a PTAS for machine scheduling. Herein a configuration describes a possible placement on one of the target machines, and the IP is used to chose suitable configurations covering the jobs. We give an augmented IP formulation, which we call the module configuration IP. It can be described within the framework of n-fold integer programming and therefore be solved efficiently. As an application, we consider variants of machine scheduling with setup times. For instance, we investigate the case that jobs can be split and scheduled on multiple machines. However, before a part of a job can be processed an uninterrupted setup depending on the job has to be paid. For both of the variants that jobs can be executed in parallel or not, we obtain PTAS results. Previously, only constant factor approximations of 5/3 and 4/3 + ϵ respectively were known.

■ WB-16

Wednesday, 10:40-12:00 - Schilthorn

Health Care Systems/Pandemics

Stream: Health Care Management
Invited session
Chair: *Marion Rauner*

1 - Resilience in Health Care Systems: Implications for Austria
Marion Rauner, Doris Behrens, Margit Sommersguter-Reichmann, Bernhard Rupp, Bernhard Schwarz

Resilient Health Care Systems are essential for advanced policy decision makers. First, we discuss main components of resilience. Next, we generally analyze the complexity of health care systems from a system theory and policy modelling view. Then, we focus on the Austrian health care system and the related components to illustrate critical issues of resilience such as key interfaces, financial incentives, critical resources, and prevention. Finally, we summarize areas for OR health care policy making to foster resiliency.

2 - A Stochastic Optimisation Model to Support Cybersecurity within the UK National Health Service
Emilia Grass, Christina Pagel, Sonya Crowe, Saira Ghafur

Over the past decade there has been a surge of new digital technologies being used in healthcare to help improve the delivery and access of care. At the same time the number of cyber-attacks on healthcare has significantly increased, especially during the current COVID-19 pandemic, posing a threat to the functionality of hospitals and the safety of patients. Therefore, it is vital to be as prepared as possible for the ever-evolving cyber threats. The inherent uncertainty makes it very difficult to plan for future cyber incidents. Stochastic programming can efficiently support decision making by taking uncertainties into account. We propose a two-stage stochastic model to improve the cyber resilience of a healthcare provider by selecting a set of efficient countermeasures in preparation for upcoming cyber incidents. To be optimally equipped even for low-probability high-impact attacks we propose a second optimisation model incorporating the risk measure Conditional Value-at-Risk. Numerical tests highlight the importance of both modelling approaches and reveal what types of countermeasures are most important to increase cybersecurity in the healthcare sector.

3 - Routing Solutions to help in Pandemic Outbreaks: A Case Study
Helena Ramalhinho Lourenco, Pedro Martins, Antonio Trigo

The Covid-19 Pandemic led to a challenge in many Social and Health Organizations that need to implement solutions and responses to new problems, or old ones in a higher dimension, in a very short time. In this work, we propose a simple routing system that can be used in any organization that needs to plan the collection or distribution of products during the pandemic. Several organizations collaborated with the researcher team, among them: Creu Roja (Red Cross) to deliver food and first-necessity products to families in quarantine; Banc d'Aliments to distribute food to social restaurants; and medical organizations to collect Covid-19 samples or to distribute the vaccines to the vaccination points. All these problems can be seen as applications of the Capacitated Vehicle Routing Problem, in the open and close versions. We have implemented an Iterated Local Search algorithm and decided to incorporate it in Microsoft Excel and Microsoft Bing Maps to facilitate its applicability. In these organizations, the planning is usually done by volunteers or no-expert planners, therefore the application must be easy to use. We describe real applications in the city of Barcelona and numerical results of several applications (with pseudo-real data, due to confidential reasons). We will also discuss the implications and benefits of this tool from the point of view of the mentioned organizations and their users.

4 - Covid-19 triage in the emergency department
Christina Bartenschlager

The corona pandemic has pushed many hospitals to their capacity limits. Therefore, a possible triage of patients has been discussed controversially again and again. We examine the performance of the triage algorithm of Pin et al. (2020), which is considered a guideline for many emergency departments in Germany, e. g. also the University Hospital of Augsburg, based on a dataset with more than 4,000 patients. The results serve as a benchmark for our AI-based optimization proposals of the existing algorithm. First results show the significant optimization potential of Machine Learning techniques in Covid-19 triage regarding both, sensitivity and specificity.

Wednesday, 13:00-14:20

■ WC-04

Wednesday, 13:00-14:20 - Eiger

Robust Discrete Optimization

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Stefan Lendl*

1 - Recoverable Robust Representatives Selection Problems with Discrete Budgeted Uncertainty
Lasse Wulf, *Marc Goerigk*, *Stefan Lendl*

We analyze recoverable robust optimization for a class of selection problems.

The aim is to choose a fixed number of items (the "representatives") from several disjoint sets, such that the worst-case costs after taking a recovery action are as small as possible.

The uncertainty is modeled as a discrete budgeted set, where the adversary can increase the costs of a fixed number of items. While special cases of this problem have been studied before, its complexity has remained open since it was first mentioned in 2011 as an open problem in the PhD thesis of C. Büsing.

We make several contributions towards closing this gap. We show that the problem is NP-hard and identify a special case that remains solvable in polynomial time. We also provide a compact mixed-integer programming formulation.

With our methods, we can also show NP-hardness of the SELECTION problem with discrete budgeted uncertainity, both in the setting of recoverable robust optimization, as well as two-stage robust optimization.

2 - Robust optimization with scenarios using belief functions
Adam Kasperski, *Romain Guillaume*, *Pawel Zielinski*

A class of optimization problems with uncertain parameters is considered. The uncertainty is specified by providing a scenario set containing a finite number of parameter realizations, called scenarios. It is assumed that additional knowledge about scenarios is modeled by specifying a mass function, which defines a belief function in scenario set. According to Dempster-Shafer theory of evidence, this belief function encodes a family of probability distributions in scenario set. Using distributionally robust approach, the uncertain objective function or uncertain constraint right-hand side is replaced with the expected value with respect to the worst probability distribution encoded by the belief function. Some connections of the proposed model with known approaches are shown. In particular the model generalizes the robust min-max approach as well as some owa-minimization problems. Various computational properties of the resulting optimization problem are presented.

3 - Two-Stage Uncertainty for Two-Stage Robust Optimization Problems
Marc Goerigk, *Stefan Lendl*, *Lasse Wulf*

Classic two-stage robust optimization problems with cost uncertainty are of the form min-max-min, where we first choose a partial solution, then the adversary selects a scenario, and we can finally react by completing the first-stage solution. In this setting, the adversary costs usually affect the decisions we make in the second stage, meaning that such problems are not direct generalizations of one-stage min-max problems.

In this talk we consider a new variant of two-stage problems, where the adversary affects variables that were determined in the previous stage. Thus, both the decision maker and the adversary have two-stage variables. This setting is a direct generalization of one-stage problems. It can also be seen as a problem with explorable uncertainty, where we can pack some items to gain information on the cost scenario.

Using continuous budgeted uncertainty sets, we show that a wide range of combinatorial problems can still be solved in polynomial time in this setting, despite the apparent increase in problem complexity. However, problems become hard to solve when using discrete budgeted uncertainty sets.

4 - Robust Appointment Scheduling with Heterogeneous Costs
Andreas S. Schulz, Rajan Udwani

Designing simple appointment systems that, under uncertainty in service times, try to achieve high utilization of expensive medical equipment and personnel and short waiting time for patients has long been a challenging problem in health care. We consider a robust version of the appointment scheduling problem, introduced by Mittal et al. (2014), to find easy-to-use and straightforward algorithms. Previous work focused on the particular case where per-unit costs due to under-utilization of equipment/personnel are homogeneous, i.e., costs are linear and identical. We consider the heterogeneous case and devise an LP with a simple closed-form solution. This solution yields the first constant-factor approximation for the problem. We also find special cases beyond homogeneous costs where the LP leads to closed-form optimal schedules. Our approach and results extend more generally to convex piecewise linear costs. For the case where the order of patients is changeable, we focus on linear costs and show that the problem is strongly NP-hard when the under-utilization costs are heterogeneous. It was previously shown that an EPTAS exists for changeable orders with homogeneous under-utilization costs. We instead find a straightforward, ratio-based ordering that is 1.0604 approximate.

■ WC-05

Wednesday, 13:00-14:20 - Mönch

Software for OR - Solvers II

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Renke Kuhlmann*
Chair: *Michael Bussieck*

1 - ENTMOOT: A Framework for Optimization over Ensemble Tree Models
Alexander Thebelt, Jan Kronqvist, Miten Mistry, Robert M. Lee, Nathan Sudermann-Merx, David Walz, Ruth Misener

We present the ENsemble Tree MOdel Optimization Tool (ENTMOOT) a comprehensive black-box optimization tool that combines tree-based models with deterministic global optimization. Tree-based models, e.g., gradient-boosted trees, (i) give valuable information regarding feature importance, (ii) scale well for large amounts of data, (iii) are capable to handle various data types and (iv) have excellent local and global prediction capabilities depending on the number of trees and interaction depth used. Inside a Bayesian optimization loop we combine such tree ensembles with suitable uncertainty measures into an acquisition function to trade-off exploitation and exploration when proposing new query points for the black-box function at hand. While other approaches rely on stochastic optimization methods to minimize the acquisition function, ENTMOOT uses tight mixed-integer linear problem encodings of tree ensembles in combination with off-the-shelf branch-and-bound solvers, to identify the best acquisition trade-off possible. Some key features of ENTMOOT include: (i) various options of novel continuous and discrete uncertainty measures based on distance metrics and proximity within the binary trees of the tree ensemble, (ii) including explicit constraints on the input variables, (iii) hierarchical acquisition functions that explicitly leverage global solvers for simplified hyperparameter tuning and (iv) multi-objective optimization. In an extensive numerical study, we show ENTMOOT's competitive performance compared to other state-of-the-art black-box optimization solvers. ENTMOOT's versatility with respect to different data types and its capability to explicitly consider domain knowledge when optimizing black-box functions has enabled various applications in industry.

2 - Yasol - A General Solver for Multistage Robust Discrete Linear Optimization Problems
Michael Hartisch, Ulf Lorenz

We present our solver Yasol that is able to solve multistage robust optimization problems with integer decision variables, a linear constraint system, and a discrete polyhedral and decision-dependent uncertainty set. At the heart of the solver a game tree search is performed that is enhanced with MIP-, QBF- and SAT-solving techniques. In order to model such problems, we use quantified integer programs (QIPs), which are integer linear programs with ordered variables that are either existentially or universally quantified. QIPs provide a very convenient framework for multistage robust optimization problems as no attention has to be paid to the decision variables' dependencies on observed scenarios during modeling. We give an introduction into QIPs, discuss problem formulations and showcase our solver.

3 - Pushing computational boundaries: Solving integrated investment planning problems for large-scale energy systems with PIPS-IPM++
Karl-Kiên Cao, Manuel Wetzel, Nils-Christian Kempke, Thorsten Koch

Energy policies for setting the course of future energy supply often rely on models of energy systems with increasing interdependencies. On the mathematical side this translates into linking variables and constraints in the structure of optimization problems. Challenges concerning limited computing resources are often tackled from the applied side since generic parallel solvers are not available. This means that modelers today aim to simplify real-world models when implementing new features, despite of lots of effort spent for improving them before. This prevents accurately modeling of all system components. We tackle this challenge by combining both domain knowledge from the application side and the solver side and demonstrate our solution for a real-world model which is practically not solvable with existing methods. Therefore, we parameterize instances of the energy system optimization model REMix having more than 700 Mio. non-zeros. For the first time, these model instances incorporate both the optimization of a full hourly operational time horizon and path-dependent long-term investment planning for the German power system. These instances are annotated in a way, that the corresponding linear problems (LPs) decompose into blocks of similar size. To solve the annotated LPs, the new interior-point solver PIPS-IPM++ is applied. It treats large numbers of linking variables and constraints using a hierarchical algorithm and enables efficient scaling on parallel hardware. In this sense, we expand the boundaries of what is computationally possible when solving LPs in energy systems analysis. Accordingly, using the best possible real-world models becomes practicable, which enables the calibration of simplified models in a domain where validation is difficult.

4 - GAMS Engine - A New System To Solve Models On Centralized Compute Resources
Stefan Mann, Frederik Proske, Hamdi Burak Usul

Algebraic modeling languages (AMLs) such as AIMMS, AMPL, and GAMS are established tools in operations research, and in many business applications.

Traditionally, personal computers have been powerful enough to solve AML model instances in acceptable time, especially when using highly efficient commercial solvers. Exceptions can be observed, for example in the energy systems modelling field, where very large, memory bound LPs have to be solved, which are beyond the capabilities of ordinary desktop computers. Modelers in those areas have access to qualified IT staff, who can implement custom scheduling systems to run large optimization jobs on central compute resources, or increasingly in the cloud.

However, with the general trend towards data based decision making, the computational requirements of AML models in other fields grow faster than the performance increase of PC hardware. Therefore, many users outside of the typical memory hungry fields now regularly hit the limits of personal computers and would benefit from the use of more powerful compute resources. To offer a solution to this problem, we have developed GAMS Engine, which is a powerful GAMS job-scheduling system.

Central to Engine is a modern REST API, which provides the interface to a scalable Kubernetes based system of services, providing API, database, queue, and a configurable number of GAMS workers. In this presentation we will explain the system architecture, it's benefits, and demonstrate how to communicate with the REST API.

■ WC-06

Wednesday, 13:00-14:20 - Jungfrau

Software for OR - Parallel (MIN)LP

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Yuji Shinano*

1 - The Generalized Ubiquity Generator (UG) Framework – Towards UG version 1.0
Yuji Shinano

The current generation of supercomputers will have over a million cores. The Ubiquity Generator (UG) framework is originally designed to parallelize state-of-the-art branch-and-bound based solvers. Towards UG version 1.0, it is redesigned to the Generalized UG framework. The goal of the Generalized UG framework is to make massive parallelization available to a wide range of optimization solvers and to enable easier use on a broader range of optimization applications on more cores. The UG Framework successfully parallelized Mixed Integer Linear Programming and combinatorial optimization problems, such as the Steiner Tree Problem in Graphs and the Shortest Vector Problem, using more than 100,000 cores. In this talk, we will present the Generalized UG and also introduce success stories for several applications.

2 - Solving Challenging Large Scale QAPs with DNN-based Branch-and-bound Method
Koichi Fujii, Naoki Ito, Sunyoung Kim, Masakazu Kojima, Hans Mittelmann, Yuji Shinano, Kim-Chuan Toh

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 (UG) framework which can utilize more than 100,000. Lower bounding procedures incorporated in the branch-and-bound method play a crucial role in solving the problems. To obtain a strong and accurate lower bound, we employ the Lagrangian doubly nonnegative (DNN) relaxation and the Newton-bracketing method developed by the authors' group. In this talk, we describe some basic tools including the lower bounding procedure and branching rules using the information of primal/dual DNN relaxation. We present some preliminary numerical results on some QAP instances from QAPLIB, including tai30a and sko42 from QAPLIB, which have been solved for the first time.

3 - Parallel solution of Steiner tree and related problems
Daniel Rehfeldt, Thorsten Koch, Yuji Shinano

The Steiner tree problem in graphs (SPG) is one of the most studied problems in combinatorial optimization and computer science. The current state-of-the-art solver for SPG is SCIP-Jack—being often millions of times faster than general mixed-integer programming solvers. Furthermore, SCIP-Jack can handle many related problems. This talk discusses key components of SCIP-Jack, with a focus on the latest algorithmic developments. Furthermore, the parallelization of several algorithms used within SCIP-Jack is disscussed. Finally, we provide recent computational results, both for the sequential and parallel versions of SCIP-JACK.

4 - PIPS-IPM++ - A Parallel Interior-Point Method for Solving Large-Scale Doubly Bordered Block Diagonal LPs
Nils-Christian Kempke, Thorsten Koch, Charlie Vanaret, Karl-Kiên Cao, Manuel Wetzel

The current shift of energy systems in several European countries towards sustainable, renewable technologies comes with a massive decentralization and a concomitant increase in the scale of realistic energy models. The resulting large-scale linear programs (LPs) often contain several hundred million constraints and variables. These models can take prohibitively long to solve for state-of-the-art commercial solvers and even exceed the capacities of a single desktop machine. Against this backdrop, the research project UNSEEN has been launched to develop methods for solving currently intractable energy optimization problems. The optimization problem exhibit a block-diagonal structure with both linking constraints and linking variables. For solving LPs with this doubly bordered structure, we developed the parallel interior-point method (IPM) PIPS-IPM++. Our solver exploits the problem structure to parallelize the linear algebra kernel in classical IPMs for LP. However, PIPS-IPM++'s performance crucially correlates with the number of linking constraints and variables present in the model. Traditionally, linking parts of the problem form a sequential bottleneck in our algorithm, rendering instances with a high share of linking structure inefficient to solve by our approach. We implemented a series of techniques to overcome this shortcoming. In this talk, we present the latest algorithmic features of our solver, including its structure exploiting capabilities and a new hierarchical solution approach. We demonstrate PIPS-IPM++'s capabilities on several real-world energy system problems, solved with the supercomputer at JSC (Juelich).

■ WC-07

Wednesday, 13:00-14:20 - Niesen

Matheuristics and Scheduling

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *Roberto Montemanni*

1 - A MathHeuristic for a real-life Pallet Loading Problem
Matteo Magnani, Mauro Dell'Amico, Luca Zanni

We consider the Pallet Loading Problem, where a set of boxes are to be packed on the smallest number of pallets, by satisfying a given set of constraints. In particular we refer to a real-life environment where each pallet is loaded with a set of layers of boxes, and both a stability constraint and a compression constraints must be respected. The stability requirement imposes: (a) to load at level k+1 a layer with total area (i.e. the sum of the areas of the boxes in the layer) not exceeding alpha times the area of the layer of level k (where alpha >= 1), and (b) to limit with a given threshold the difference between the highest and the smallest box of a layer. The compression constraint defines the maximum weight that each layer k can sustain, hence the total weight of the layers loaded over k must not exceed this value. Some kind of stability and compression constraints are considered in other works from the literature, but, to out knowledge, none is defined as in our real-life problem. We present a matheuristic approach which works in two phases. In the first one a number of layers are defined using classical 2D-Bin Packing algorithms, applied to a smart selection of boxes. In the second phase the layers are feasibly packed on the minimum number of pallets, by means of a sepcialized MILP model solved with Gurobi. Computational experiments on randomly generated and real-life instances are used to assess the effectiveness of the algorithm.

2 - Sequential testing in batches with resource constraints
Fan Yang, Ben Hermans, Nicolas Zufferey, Roel Leus

The sequential testing problem is encountered in the context of system diagnosis, and aims to examine the state of a system by performing a range of tests of the system's constituent components. Each component has a probability of working correctly and a testing cost, and the test outcomes of components are independent of each other. The testing process is interrupted as soon as the state of the system is known. The objective is to find a sequence of component tests with minimal total expected cost. The most frequently studied system to be tested is a serial system, which functions only if all its components are working.

This study considers an extension of the sequential testing problem for a serial system where components can be batched and tested together. Each test has a specific resource requirement (e.g., workers or tools), and the total requirement of tests in one batch cannot exceed the resource capacity. Besides the testing cost of each component, each batch, regardless of the number of tests that it contains (unless that number is zero), also has a fixed cost. We decide how to batch tests together and sequence the obtained batches to minimize the total expected costs. To solve this problem, we propose a linear mixed-integer programming model and a Benders decomposition procedure. Since the exact methods can only solve small instances, we also develop a matheuristic following the framework of "proximity Benders" and a tabu search procedure for large instances.

3 - Efficient Omnichannel Food Supply Chains: Optimization Strategies for In-Store Order Picking
Nicola Ognibene Pietri, Xiaochen Chou, Dominic Loske, Matthias Klumpp, Roberto Montemanni

We are witnessing an impressing increase of digitalization, and this has greatly influenced also our behaviour as consumers. This process has been further accelerated by the restrictions and fears caused by the COVID-19 pandemic. Derived from these trends, traditional brick-and-mortar grocery retailers are highly motivated to develop omnichannel solutions like Buy-Online-Pick-up-in-Store (BOPS) concepts in order to profit economically. The processing of online orders in retail stores tends to be neglected by supply chain optimization tools, but this aspect is becoming more and more central to efficient retail logistics operations due to increasing online order shares. In this paper we discuss an optimization approach based on real-life data from a German retailer with the aim of optimizing the very last operation in the chain: picking products of BOPS orders from the shelves of a store. This problem is treated as a Traveling Salesman Problem where the article positions in the shelves play the role of the cities. This can however lead to product damaging and rearranging overhead to prepare the final bags for the customers. The aim of this paper is to analyse how the introduction of precedencies during picking influences performance, turning the problem into a Sequential Ordering Problem with precedencies derived through a weighted sum that considers product attributes such as size, heaviness, density and packaging. The target is a picking strategy, heuristic in nature, able to trade-off between speed and accuracy of picking, where accuracy accounts in this context for preventing damages to goods and repackaging cost for the retailer.

4 - A Heuristic Approach for the Flying Sidekick Traveling Salesman Problem
Roberto Montemanni, Mauro Dell'Amico, Stefano Novellani

The use of drones in urban logistics is gaining more and more interest. In this paper we consider the flying sidekick traveling salesman problem, where some customers require a delivery and they can be served either by a truck or by a drone. The aim is minimizing the total time required to service all the customers. In this talk we discuss some algorithms based on branch and bound for the problem. A first contribution is an exact algorithm characterized by not completely specified solutions in the search tree, that are later fully determined by solving an Assignment Problem. Such a choice limits the size of the search tree, but on the other hand tends to weaken lower bounds. Experimental results show that the choice pays off for instances of limited size, leading to very good and consistent results in terms of speed for instances up to 10-15 customers. Note that these results are in line with the current literature. The same branch and bound algorithm is also effectively used as a subroutine for a heuristic algorithm, which is the second contribution of this work. The idea is to iteratively optimize overlapping chunks of a solution with the exact algorithms. Again, experimental results prove that such a heuristic approach is extremely competitive on large instances, being able to effectively deal with instances with up to 229 customers in a relatively short time, representing the state-of-the-art, as far as we are aware.

■ WC-08

Wednesday, 13:00-14:20 - Stockhorn

Energy and complementarity problems

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

1 - Prosumers with PV-Battery Systems in the electricity markets - a mixed complementarity approach
Felix Meurer, Marco Sebastian Breder, Michael Bucksteeg, Christoph Weber

Previous studies have shown that decentralised sector coupling and flexibility options play an important role in the integration of renewable energies into energy systems in the future. Recent developments include increased investments in PV battery systems underlining the increased importance of decentralised flexibility. At the same time, the present design of retail tariffs means that private households operate coupled PV battery systems primarily with the aim of increasing self-consumption, although the flexibility could be utilised to support the power system.

Our contribution examines in a stylised setting which adjustments to the regulatory framework can work towards a system-oriented operation of decentralised flexibilities with a focus on PV battery systems. We use the format of Mixed Complementarity Problems (MCP) to combine the optimisation calculus of decentralised actors at the retail level with cost minimisation at the wholesale market level. We use a MCP because it is particularly well suited to model economic equilibria when the value range of variables is limited, as in our case. In contrast to previous studies, we focus on the explicit representation of a retailer in our model. When considering decentralised actors, we focus on prosumers, which in our simplified setting are depicted as representative households with a PV system and battery storage. Methodologically, we work out the advantages in the better interpretability of the results of MCP compared to alternative formulations.

2 - Modeling solar prosumage: mixed complementarity problems vs. coupled linear programs
Carlos Gaete, Wolf-Peter Schill

In many electricity markets, consumers have increasing incentives to meet parts of their energy demand with self-generated electricity from solar PV. The level of self-consumption can be further increased when a battery storage system is coupled with the PV installation. This concept is referred to as "prosumage" (Hirschhausen 2017). Investment and operational decision of prosumage installations heavily depend on regulatory settings, in particular on the design of retail and feed-in tariffs. Günther et al. (2021) analyze the effects of various tariff designs on optimal PV and battery capacity choices of households in Germany. They use a mixed complementarity problem (MCP) to link a cost-minimization problem of prosumage households and a cost-minimizing dispatch problem in the wholesale market. Numerically solving this MCP, considering a full year in hourly resolution, turns out to be challenging, which limits the applicability of the model. Here, we propose an alternative approach where the two linear cost minimization problems are iteratively solved. We investigate aspects of convergence and optimality, and compare results and computational expenses to the MCP approach. Based on this, we explore possible extensions of the model setup, in particular expanding the pure dispatch wholesale market problem to a capacity expansion model.

Günther, C., Schill, W.-P., and Zerrahn, A. (2021): Prosumage of solar electricity: Tariff design, capacity investments, and power sector effects. Energy Policy 152, 112168, https://doi.org/10.1016/j.enpol.2021.112168. Von Hirschhausen, C. (2017): Prosumage and the future regulation of utilities: An introduction. Economics of Energy & Environmental Policy, 6(1), 1-6. https://doi.org/10.5547/2160-5890.6.1.cvh

3 - Flexibility from prosumers for congestion management - A conceptual mixed complementarity programming approach
Hannes Hobbie, Matthew Schmidt

The transformation of the energy system entails impacts for the future operation of power grids. Traditional congestion management involves the activation of large-scale conventional power plants. With the gradual phase out of these technologies and the development towards a distributed and renewable-based generation structure with an increasing electrification of heating and mobility applications, new solutions are needed to provide transmission system operators with sufficient redispatch capacities. This transformation must exploit these technologies and engage the participation of end-users who typically own the applications but have limited access to wholesale markets. The concept of regional flexibility markets and so-called aggregators which have access to end-user applications by way of smart grids and manage the bundled energy procurement and marketing is anticipated to play an important role.

Besides technical challenges, market design issues and preferences of individual stakeholders exert a strong impact on possible solutions. Whereas grid operators seek to implement congestion management measures in accordance with the regulatory framework on a least (system) cost basis, regional market participants as well as aggregators are characterised by competing aims and usually endeavour to maximise their own utility or profits.

Expected findings of this work provide insights on how organisation of regional flexibility provision impacts market equilibria and efficiency of future congestion management and how the different decision levels associated with the outlined concept can be adequately considered in a system theoretic modelling framework. In order to incorporate these aspects the application of bi-level programming and complementarity models is proposed.

4 - Sequential Investments in Hybrid PV-Wind Systems for Hydrogen Production: A Real Options Analysis for Germany and California
Paul Fabianek, Reinhard Madlener

In this study, flexible sequential investments in hybrid solar PV-wind-hydrogen generation plants with grid connection are analyzed by means of real options analysis for their profitability and optimal timing to invest (sequential investment problem). In this way, decision-making in two growing markets with high uncertainty are facilitated. The technical, economic and regulatory framework conditions in Germany and California are studied in detail. In order to maximize the share of renewable electricity for the production of hydrogen by electrolysis, the optimal combination of PV and wind energy plants is scrutinized. The conversion of hydrogen into electricity is not part of the study. Whether and when investments or expansions should be made, and which hydrogen sales opportunities are profitable, is examined in detail. The role of subsidies is taken into account in the analysis as well. The results from the real options analysis provide new insights into the hydrogen market development in the two states relevant for a variety of different decision-makers.

■ WC-09

Wednesday, 13:00-14:20 - Gantrisch

Simulation-based Analysis

Stream: Systems Modeling and Simulation
Invited session
Chair: *Christian Stummer*
Chair: *Klaus Altendorfer*

1 - How much can electric aircraft contribute to reaching Flightpath 2050 CO2 emissions goal? A system dynamics approach for European short haul flights

Chetan Talwar, Imke Joormann

The airline industry in the recent past has been targeted for its impact on climate change. In 2012, the Advisory Council for Aeronautics Research in Europe (ACARE) introduced Flightpath 2050 aiming at reducing the CO2 emissions by 75 % until 2050. In recent studies, electric aircraft has been identified as a potential contributor in reaching the CO2 emission targets. The purpose of this study is to assess the impact of electric aircraft for short haul flights on reaching the Flightpath 2050 CO2 emissions goal using different policy scenarios within the EU. We develop a system dynamics model of the air transport system (ATS), consisting of the interaction between three major segments, namely air travel demand, airline industry and aircraft manufacturers. The model is run for the time period from 1991 to 2050, where electric aircraft are introduced in the year 2035. We simulate the behavior of the ATS under different policy scenarios, e.g., introduction of jet fuel tax, electricity subsidy, seat tax or fleet restriction policy, to test their influence on electric aircraft adoption rates. The results of the analysis suggest that implementing an individual policy is not enough to reach the Flightpath 2050 CO2 emission goal, whereas by combining policies the goal was reached. Specifically, the combination of a fleet restriction policy with electricity subsidy demonstrates a higher electric aircraft adoption rate than that of other combinations. On the other hand, sensitivity analysis shows that combinations with electricity subsidy display higher volatility in the CO2 emissions interval. The main reason for this sensitivity is due to the uncertainty in cost pertaining to electric aircraft development parameters.

2 - Optimizing patient flow in a forensic clinic via discrete event simulation

Samuel Kolb, Peter Wermuth, Harold Tiemessen, Jörg Forrer

We consider a forensic clinic with multiple treatment stations and elective and urgent patient arrivals. Elective patients are awaiting their treatment outside the clinic and are called in when a treatment place becomes available. Typically, forensic clinics are bottleneck leading to long waiting lists and significant waiting times. Urgent patient arrivals arise due to crisis interventions. They happen unannounced and randomly. Based on their current skill level and risk potential, each patient is assigned a privilege level 0 - 10. During their stay at the forensic clinic (most) patients will make progress and slowly climb to higher privilege levels. However, it also happens that due to bad behavior, patients get degraded. To enable best possible treatment and create a safe environment for patients and employees, each station only admits patients with a certain small range of privilege levels. A scenario with many stations, each covering a small range of privilege levels, performs well on quality of treatment, but relatively poor on economic key performance indicators such as utilization rate and average waiting time, due to limited resource pooling and bottlenecks. We developed a discrete event simulation model and simple but effective admission rules to optimize patient flow, taking into account providing adequate treatment, utilization of all stations, average waiting times inside and outside the clinic and - last but not least - rejection rates of urgent patient arrivals. Based on real-life data we evaluated various future scenarios and provided valuable decision support.

3 - Modeling consumers' heterogeneity and individuality can make a difference: Insights from a simulation experiment

Markus Günther, Christian Stummer

More often than not, models in innovation diffusion research either do not account for consumers explicitly (e.g., in the Bass model) or do focus on a few representative consumers only (e.g., in the model by Rogers). However, consumer in real markets are considerably more diverse and heterogeneous. Moreover, the behavior of consumers is not only driven by their characteristics (e.g., innovativeness, preferences for product attributes, or susceptibility to normative social influence) but their attitude is also altered by their individual past experience (e.g., first-hand experience with products), individual actions and interactions (e.g., information received through word of mouth) or the actual social influence being exerted by their current peers. Thus, these factors differ between consumers due to previous and dynamic events, which influence their innovation adoption behavior. In our talk, we demonstrate possible effects of heterogeneity as well as individuality when modeling market diffusion of innovations by means of a (computational) simulation experiment. To this end, we first translated the basic Bass model to an agent-based model. Then, we set up a generic market and ran the simulation for two settings. In the first setting, all consumer agents have the same characteristics (i.e., they have identical parameter values for p and q), whereas in the second setting consumer agents differ in this respect. Thus, we explicitly account for heterogeneity although the average over all agents equals the values used in the first setting. In order to also take into consideration (a certain degree of) individuality we finally added a social network, that is, in this setting it matters with which (and with how many) peers a specific consumer agent is connected.

4 - Combining Causal Loop Diagrams, Behavior-Over-Time Graphs, and Domain-Specific Languages to Structure and Explore Complex Decision-Making Situations

Adrian Stämpfli

Causal Loop Diagrams (CLDs) are a flexible and valuable tool for diagramming the feedback structure of systems. In strategic decision-making and management, we use CLDs to structure and explore complex problems, to foster learning, as a basis for simulation models, and to communicate simulation results. Often we combine CLDs with Behavior-Over-Time Graphs (BOTGs) as an initial step to understanding the dynamic patterns and the quantitative scale of the problem under study. BOTGs are especially helpful in capturing dynamic, quantitative hypotheses about the problem at hand. As BOTGs illustrate the dynamic and quantitative scale of a variable, feedback loop, or a complete CLD, they help foster thinking about the structure-behavior relationships relevant to the problem under study.

Following up on our earlier research, we present a Domain-Specific Language (DSL) that allows generating visual representations of CLDs enriched with BOTGs. With the enhanced DSL, we can illustrate the structure, dynamic patterns, and quantitative scale of the problem under study step-by-step, allowing exploration and reflection by a broad audience.

The DSL approach lowers technical barriers and is accessible to modeling experts with little programming experience. A simple mechanism allows deploying the visual representations in the form of small web apps. We implemented the DSL in R, an open-source programming language and software environment designed for statistical computing, data science, and graphics, uniquely well suited to host DSLs.

A first application uses the DSL to generate small web apps showcasing CLDs and BOTGs of typical burnout-dynamics. Possible further developments include simulation capabilities.

■ WC-10

Wednesday, 13:00-14:20 - Schreckhorn

Liner Shipping

Stream: Logistics and Freight Transportation
Invited session
Chair: *Nicolas Rückert*

1 - The Stochastic Liner Shipping Fleet Repositioning Problem with Uncertain Container Demands and Travel Times
Jana Ksciuk, Stefan Kuhlemann, Kevin Tierney, Achim Koberstein

Liner shipping repositioning is the costly process of moving container ships between services in a liner shipping network to adjust the network to the changing demands of customers. Existing deterministic models for the liner shipping fleet repositioning problem (LSFRP) ignore the inherent uncertainty present in the input parameters. Assuming these parameters are deterministic could lead to extra costs when plans computed by the deterministic model are realized. We introduce an optimization model for the stochastic LSFRP that handles uncertainty regarding container demands and ship travel times. We extend existing LSFRP instances with uncertain parameters and use this new dataset to evaluate our model. We demonstrate the influence of uncertain demand and travel times on the resulting repositioning plans. Furthermore, we show that stochastic optimization generates solutions yielding up to ten times higher expected values and more robust solutions, measured against the CVaR90 objective, for decision-makers in the liner shipping industry compared to the application of deterministic optimization in the literature.

2 - Service independent liner shipping vessel routing
Daniel Wetzel, Kevin Tierney

Liner shipping networks are a central feature of modern supply chains that consist of cyclical, periodic services operated by container ships. While this specialized, cyclical structure eases planning for both shipper and carrier, the available time windows at ports can lead to inefficient sailings within a service. We propose to change the way ships sail on their predefined schedules, allowing them to move between services to avoid inefficient connections. From the view of a shipper, the cyclical and periodic properties of the services still hold, and the liner carrier can offer a more efficient overall network. The resulting optimization problem consists of a cargo allocation problem (i.e., container routing) as well as a vessel routing problem, resulting in large and difficult instances. We use mixed-integer linear programming to model this problem and use column generation for efficiently finding solutions and compare them to their standard cyclical schedule equivalents.

3 - Robust Multistage Yard Crane Scheduling in Container Terminals
Tobias Marx, Michael Hartisch, Ulf Lorenz

We deal with robust yard crane scheduling inside a storage block of a container terminal. Yard cranes are often responsible for bottlenecks in the container flow of terminals. We consider scenarios with high utilization rates of the cranes, where uncertainties regarding the arrival of transport vehicles at the sea and landside of the container terminal storage blocks lead to uncertain schedules for the yard cranes. If uncertainties are not incorporated in the scheduling process, the resulting plans can quickly become suboptimal, leading to extended overall completion times that result in delays and can incur penalty costs as a consequence. We present a multistage quantified programming model that allows us to minimize the worst-case objective value by taking into account the uncertainties about the arrivals of containers at the storage block. Thereby, we minimize the total delay of the jobs, resulting from the difference between the completion dates and the due dates. In an additional approach, we consider particularly common scenarios by enhancing our model with weighted, partial deterministic equivalent programs that cover these scenarios. Furthermore, we compare our approaches with the deterministic model.

4 - Optimization of container transportation in port hinterland with trucks - Approaches to cooperation
Nicolas Rückert, Kathrin Fischer, Pauline Reinecke, Thomas Wrona

In recent years, containerized transportation has become increasingly important. According to the UNCTAD review, the annual growth rate for goods transported in containers amounts to 1.1 % in 2019. This leads to challenges for container handling in ports and hinterland transportation. At the same time, the advancing digitalization of ports and the ever-increasing amount of data available are opening up new opportunities for data-based optimization. The logistics in the hinterland of ports accounts for up to 80% of the total cost of the maritime logistics chain. Optimizing hinterland logistics offers large potential for using scarce infrastructure resources efficiently, for reducing emissions and costs, and for providing high quality hinterland services to increase competitiveness. In this presentation it is discussed how costs in hinterland container logistics with trucks can be reduced by using horizontal cooperation, i.e. by sharing and/or exchanging customer orders, and how stable cooperation can be established. Based on a literature review and expert interviews, the relevant approaches, such as compensation mechanisms, which are required for a balanced and long-term horizontal cooperation between forwarders and truckers, are identified. These approaches are integrated into a mathematical model for the operative optimization of container transportation in port hinterland with trucks. The analysis shows that different degrees of cooperation have different impact on the efficiency of the system, e.g. in terms of cost and emission reduction. The relation between the intensity of exchange of customer orders and the different objectives as efficiency and sustainability is studied and discussed, and further research needs are identified.

■ WC-11

Wednesday, 13:00-14:20 - Wildstrubel

Planning in Supply Chain and Production Management II

Stream: Supply Chain and Production Management
Invited session
Chair: *Christina Liepold*

1 - Parameterization of optimization-based order release in the context of engineer-to-order systems
Jana Plitt, Ralf Gössinger

Order release is the sub-task of production planning that initializes the execution of already accepted orders. Besides the uncertainty of order arrival, in engineer-to-order systems two further kinds of uncertainty become relevant for this task: the period of complete specification of an order (specification time uncertainty) and the manufacturing process of an order (capacity requirements uncertainty). To decide on the release of an order with incomplete specification, the order is subdivided into components such that completely specified (incompletely specified) components can be released finally (provisionally). For incompletely specified components, more information is provided at a later, yet unknown point in time. Since further information on order arrival, specification time, capacity requirements and order fulfillment becomes available with the passage of time, a MILP model embedded in a rolling horizon approach has been proposed. Thereby the values of the stochastic variables "specification time" and "capacity requirements" are estimated using chance-constraints, for which probability thresholds need to be specified in advance as parameters. In order to obtain clues for setting the parameter values in a favorable way, we conduct a full-factorial numerical study that reveals the model behavior in terms of costs and robustness. Statistical analyzes confirm a significant connection between these attributes of release plans and the parameter values. Therefore, the results of the numerical study are used to determine costs and robustness as functions of the parameter values. Analyzes of such functions enable the delimitation of areas of parameter value combinations that are dominant with respect to single or multiple objectives.

2 - Integrated Production Lot Scheduling and Transportation Planning for Vendor-Managed Inventory in industrial b2b supply relationsships with customer-specific production
Hartwig Baumgaertel, Daniel Bischof

The German automotive industry relies on established standard delivery processes, as described in the recommendation VDA5010 of the German Association of the Automotive Industry. Beneath the inventory-less standard processes JIT and JIS, one process with inventory is standardized there: the one-stage inventory delivery. It is characterized by three main properties: location of the inventory close to the customer, consignment stock, and suppliers responsibility for dispatching of replenishments according to Vendor Managed Inventory policy. This allows the supplier to coordinate his production and transportation planning, as he can produce e.g. optimal lot sizes and can reduce the number of truck rides to save cost and pollution. To realize the potential benefits of this concept, the supplier must store the produced parts directly in a transport unit, e.g. a swap body or a semi-trailer. The characteristics of this situation differs considerably from the settings of known OR models for VMI. The Production Routing Problem and its derivatives consider perishable goods, which are transported to many customers each day. Hence, they treat the product as commodity, do not distinguish part numbers or variants, and do not consider lot scheduling or production capacity. On the other hand, they solve complete Vehicle Routing Problems but mostly only with one vehicle type. We provide a model that simultaneously plans lot production and transport rides, fulfilling the min and max level requirements in the inventory. An extensive literature study delimits our problem from existing literature. The model is implemented in OPL in CPLEX Optimization Studio. First experimental results of test scenarios are shown, and further questions will be raised.

3 - Reducing product complexity in life sciences: A conic-integer programing approach and heuristic solution techniques
David Francas, Enrique Hortal Segura

In pharmaceutical supply chains, most of the product complexity arises at the packaging level. Due to regulatory requirements and marketing considerations, a common practice is to rely on country-specific products that have market authorization in just one market. However, this practice comes at the expense of lower flexibility, higher inventory levels, and increased supply chain costs, which is a particular concern for high-value, low-volume drug brands. Motivated by the case of a major pharmaceutical company, we develop an optimization approach that identifies markets that should be served together via so-called multi-country packs. We model the decision problem as a mathematical program that considers inventory holding, setup, market compatibility, and complexity costs along with regulatory constraints. We show how to formulate this problem as a conic quadratic mixed-integer program that can be solved by standard optimization packages. Furthermore, we develop a simulated annealing algorithm that can solve large-size problems heuristically.

4 - Production as a Service: On the Impact of Partial Production Capacity Sharing
Christina Liepold, Okan Arslan, Gilbert Laporte, Maximilian Schiffer

Cloud manufacturing - as one of the trends subsumed under Industry 4.0 - influences production and manufacturing areas as it transforms the process of resource utilization into a shared on-demand service. Central for cloud manufacturing is the production as a service (PaaS) paradigm that establishes resource control and collaboration through cloud computing and service-oriented technologies. PaaS allows intermediaries to coordinate supply and demand of idle production capacities, thus enabling horizontal collaboration through the exchange of idle production capacity. Particularly smaller enterprises profit from PaaS as it enables them to actively participate in the procurement process without depending on established long-term supplier contracts. Current practical implementations of PaaS use multiple steps for connecting buyers and suppliers through a platform; intermediaries treat each demand request individually and subsequently contact their pool of suppliers. Against this background, we study a novel, optimization-based approach towards PaaS mechanisms and develop a combinatorial exchange model for shared production capacities among multiple suppliers and buyers. To this end, we adapt the winner determination problem from procurement auction settings. We use this model to analyze payoffs for all parties involved as well as to analyze the influence of market size and buyer-supplier ratio. Both the supplier and buyer payoffs depend on the market structure, with a fractioned supplier side leading to higher buyer and lower supplier payoffs, while the intermediary payoffs remain relatively stable. We also find that a larger market size mitigates the distribution of payoffs between buying and supplying entities.

■ WC-12

Wednesday, 13:00-14:20 - Faulhorn

Crew Scheduling in Public Transport

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

1 - Integrated Resource Scheduling in Public Transport Planning Considering the Decision Levels Timetabling, Vehicle Scheduling, and Crew Scheduling
Bastian Amberg, Boris Amberg

In this work, we investigate integrated resource scheduling in public transport planning considering the three decision levels timetabling, vehicle scheduling, and crew scheduling. The integrated consideration enables additional degrees of freedom for vehicle and crew scheduling. We propose a column generation-based solution approach for cost-efficient and robust integrated vehicle and crew scheduling that simultaneously considers cost-efficiency, delay-tolerance, and possible timetable modifications. The overall approach aims at minimizing both planned costs and possible delay propagation by means of (controlled) trip shifting. In addition to integrated vehicle and crew scheduling, controlled trip shifting is used to slightly modify both departure and arrival times of particular trips without changing their duration while the original timetable structure is preserved as far as possible, e.g., original headways between consecutive trips of a line and the quality of passenger connections. The presented solution framework allows for operational and tactical planning decisions. In a computational study, we compare the performance of different variants of the proposed solution approach on real-world data sets. The variants take cost-efficiency, delay-tolerance, and timetable preservation into account to varying degrees. We demonstrate the benefits of controlled trip shifting on the achievable solution quality.

2 - Fixed set search and reactive tabu search applied to crew rostering in public transport
Liping Ge, Raka Jovanovic, Stefan Voss, Lin Xie

The crew rostering problem (CRP) in public transport aims at determining schedules for the drivers while observing operational constraints derived from legal and contractual relations. In a multi-objective setting various concerns in the interests of different stakeholders (management of bus companies, drivers, customers) need to be considered. We attempt to solve the multi-objective crew rostering problem by means of various metaheuristics while tackling the weighted sum of all objectives as well as approaching the Pareto front. The methods under consideration focus on the newly developed fixed set search (FSS) approach as well as a somewhat neglected tabu search implementation. FSS is a novel metaheuristic adding a learning mechanism to enhanced greedy approaches. This may be done by starting with a greedy randomized adaptive search procedure (GRASP) and then using consistent chains or overlapping elite-solution parts to achieve an intelligent interplay between intensification and diversification of the search. The same interplay can be achieved within the reactive tabu search (RTS) once hybridized with standard simulated annealing. Numerical results are provided for a set of 15 real-world instances from literature for personalized crew rostering for which the number of assigned duties varies between 1313 and 19486 and the number of drivers between 48 and 629. Both approaches, FSS and RTS, are favorably used to improve existing crew rostering approaches from literature, notably those incorporating ant colony optimization as well as traditional tabu search. Moreover, a comparison with the results from using a commercial solver is provided in the weighted case.

3 - Driver Routing and Scheduling in Long-Distance Bus Networks
Pia Ammann, Rainer Kolisch, Maximilian Schiffer

The liberalization of the European long-distance bus market caused rapid growth in demand for intercity coach travel in recent years, resulting in competition between numerous private coach companies. In this highly competitive environment, a company only survives by keeping operational costs at a minimum. With driver wages being a major cost share, efficient scheduling and routing, which keeps the number of drivers as low as possible, remains a crucial planning task. Similar problems have already been addressed for airline crew scheduling, railway timetabling, truck driver scheduling, and urban bus services, but research on driver scheduling in intercity bus networks is still scarce. Against this background, we study driver routing and scheduling in long-distance bus networks. While our problem resembles a truck driver routing and scheduling problem, it bears several additional characteristics, e.g., drivers may be exchanged between buses en routes. Indeed, these exchanges may occur at arbitrary intermediate stops such that our problem contains additional synchronization constraints. We present a mathematical model defined on a time-expanded multi-digraph and derive bounds for the total number of drivers required. Moreover, we develop an exact algorithmic framework that combines a MIP with a local search procedure and destructive bound improvement. We apply this hybrid approach to real-world data from one of Europe's leading coach companies. Compared to standalone MIP solvers, our approach improves runtimes and solution quality significantly. Furthermore, we show that our approach outperforms current approaches used in practice and yields significant cost and time savings.

4 - An Integrated Solution Approach for Crew Scheduling
Stefan Frank, Ulrike John

Personnel costs play a huge role in the airline industry. In this paper, the Crew Scheduling Problem is considered. Due to the high complexity of the problem, the solving process is mostly divided into two phases, which are solved one after the other: Crew Pairing and Crew Rostering. As both sequentially solved sub-problems have different, and partly conflicting goals, improvements can be achieved by simultaneously solving these two problems with an integrated approach. This method is investigated within this contribution. For this purpose, we give detailed insights to this problem class of Crew Scheduling with the two sub-problems as well as an overview of the solution methods in this field. We present the models (mixed integer linear programs) of the two sub-problems and the developed Genetic Algorithms for both the sequential and the integrated approach. The resulting methods were tested on real-life instances of a North American airline. The results show that an integrated approach can provide better solutions in terms of cost minimization compared to a sequential one. This considers also balances for crew member wishes. In addition, our further work will focus on evaluating the results with respect to their robustness, since robust planning can be affected by the increased occurrence of disruptions in air traffic.

■ WC-13

Wednesday, 13:00-14:20 - Blüemlisalp

Games on Networks

Stream: Game Theory and Behavioral Management
Invited session
Chair: *Dario Paccagnan*

1 - Two-Stage Facility Location Games with Strategic Clients and Facilities
Simon Krogmann

We consider non-cooperative facility location games where both facilities and clients act strategically and heavily influence each other. This contrasts established game-theoretic facility location models with non-strategic clients that simply select the closest opened facility. In our model, every facility location has a set of attracted clients and each client has a set of shopping locations and a weight that corresponds to her spending capacity. Facility agents selfishly select a location for opening their facility to maximize the attracted total spending capacity, whereas clients strategically decide how to distribute their spending capacity among the opened facilities in their shopping range. We focus on a natural client behavior similar to classical load balancing: our selfish clients aim for a distribution that minimizes their maximum waiting times for getting serviced, where a facility's waiting time corresponds to its total attracted client weight. We show that subgame perfect equilibria exist and give almost tight constant bounds on the Price of Anarchy and the Price of Stability, which even hold for a broader class of games with arbitrary client behavior. Since facilities and clients influence each other, it is crucial for the facilities to anticipate the selfish clients' behavior when selecting their location. For this, we provide an efficient algorithm that also implies an efficient check for equilibrium. Finally, we show that computing a socially optimal facility placement is NP-hard and that this result holds for all feasible client weight distributions.

2 - The Flip Schelling Process on Random Geometric and Erdös-Rényi Graphs
Louise Molitor

Schelling's classical segregation model gives a coherent explanation for the wide-spread phenomenon of residential segregation. We consider an agent-based saturated open-city variant, the Flip Schelling Process (FSP), in which agents, placed on a graph, have one out of two types and, based on the predominant type in their neighborhood, decide whether to changes their types; similar to a new agent arriving as soon as another agent leaves the vertex. We investigate the probability that an edge u,v is monochrome, i.e., that both vertices u and v have the same type in the FSP, and we provide a general framework for analyzing the influence of the underlying graph topology on residential segregation. In particular, for two adjacent vertices, we show that a highly decisive common neighborhood, i.e., a common neighborhood where the absolute value of the difference between the number of vertices with different types is high, supports segregation and moreover, that large common neighborhoods are more decisive. As an application, we study the expected behavior of the FSP on two common random graph models with and without geometry: (1) For random geometric graphs, we show that the existence of an edge u,v makes a highly decisive common neighborhood for u and v more likely. Based on this, we prove the existence of a constant c>0 such that the expected fraction of monochrome edges after the FSP is at least 1/2+c. (2) For Erdös-Rényi graphs we show that large common neighborhoods are unlikely and that the expected fraction of monochrome edges after the FSP is at most 1/2 + o(1). Our results indicate that the cluster structure of the underlying graph has a significant impact on the obtained segregation strength.

3 - Efficiency and Stability in Euclidean Network Design
Anna Melnichenko

Network Design problems typically ask for a minimum cost subnetwork from a given host network. This classical point-of-view assumes a central authority enforcing the optimum solution. But how should networks be designed to cope with selfish agents that own parts of the network? In this setting, minimum cost networks may be very unstable in that agents will deviate from a proposed solution if this decreases their individual cost. Hence, designed networks should be both efficient in terms of total cost and stable in terms of the agents' willingness to accept the network. We study this novel type of Network Design problem by investigating the creation of (β,)-networks, that are in β-approximate Nash equilibrium and have a total cost of at most times the optimal cost, for the recently proposed Euclidean Generalized Network Creation Game by Bilò et al. [SPAA 2019]. There, n agents corresponding to points in Euclidean space create costly edges among themselves to optimize their centrality in the created network. Our main result is a simple quadratic algorithm that computes a (β, β)-network with low β for any given set of points. Moreover, on integer grid point sets or random point sets our algorithm achieves a low constant β. Besides these results for the Euclidean model, we discuss a generalization of our algorithm to instances with arbitrary, even non-metric, edge lengths.

4 - In Congestion Games, Taxes Achieve Optimal Approximation
Dario Paccagnan, Martin Gairing

We consider the problem of minimizing social cost in atomic congestion games and show, perhaps surprisingly, that efficiently computed taxation mechanisms yield the same performance achievable by the best polynomial time algorithm, even when the latter has full control over the players' actions. It follows that no other tractable approach geared at incentivizing desirable system behavior can improve upon this result, regardless of whether it is based on taxations, coordination mechanisms, information provision, or any other principle. In short: judiciously chosen taxes achieve optimal approximation.

Three technical contributions underpin this conclusion. First, we show that computing the minimum social cost is NP-hard to approximate within any factor smaller than a given expression depending solely on the class of admissible resource costs. Second, we design a tractable taxation mechanism whose efficiency (price of anarchy) matches the hardness factor, and, thus, is optimal. As these results extend to coarse correlated equilibria, any no-regret algorithm inherits the same performances, allowing us to devise polynomial time approximation algorithms with optimal performance.

■ WC-14

Wednesday, 13:00-14:20 - Wetterhorn

Decision Support for Location and Routing Problems

Stream: Decision Analysis and Support
Invited session
Chair: *Meritxell Pacheco Paneque*

1 - A digital twin based decision support system for dynamic vehicle routing problems
Ulrike Ritzinger, Hannes Koller, Jakob Puchinger

The research on transportation problems is strongly motivated by real problems. One important industry is the courier, express, and parcel (CEP) market. Recent developments are the growth of the CEP market, the increasing expectations in customer services, and the new technological advances like tracking information, data storage and mobile communication. Modern decision support systems (DSS) are therefore expected to provide real-time decision-making and require fast reactions to changes in the system. Although literature of dynamic vehicle routing problems (DVRPs) exists, further challenges have to be considered when dealing with a real-time DSS. Thus, besides the development of sophisticated optimization approaches, it is essential to provide a concept representing the real world and its dynamic behaviors. In this work, we outline a digital twin based DSS with simulation capabilities for DVRPs. We present various aspects which must be considered in a real-world DSS, in order to provide high-quality solutions within short response times. We show the implementation of a background optimization task and discuss a solution for synchronizing the current system state with the planned routes. Then, we demonstrate the advantages of integrating a simulation model into the DSS. Most importantly, this allows extensive analysis of the optimization algorithm performance in advance and facilitates systematic evaluation and algorithm tuning under simulated real-world conditions. Additionally, we show how the simulation can be used to support a human decision maker during day-to-day operation. Finally, the connection to the digital twin and its advantages are demonstrated by an example application.

2 - Frontier-based facility location analysis: definition, formulation and application

Mohsen Afsharian

Facility location analysis - as one of the central topics in operations research with a broad range of application areas in logistics and supply chain management - deals with the optimal positioning of facilities providing expected services or products to customers. We discuss how to incorporate frontier-based benchmarking into the facility location. In the proposed framework, - in addition to optimizing the spatial interaction among the facilities and the demand nodes - we aim at maximizing the efficiency of the facilities as a whole. This view is in line with the centralized control mechanism that can often be seen in applications of the location analysis: facilities are managed by a central authority who wishes to improve the efficiency of the whole system rather than maximizing the individual efficiency of each facility. The problem of maximizing the overall efficiency of the facilities is presented by a bilinear mixed-integer program. We further seek to formulate its equivalent mixed-integer linear program, which substantially simplifies its implementation. Integrating the outcome of this step into the location analysis - which also optimizes the spatial interaction in the network - results in a multi-objective mixed-integer program. Real-world data from hospitals in Germany will be used to illustrate the proposed approach.

3 - On the extension of a capacitated multi-vehicle covering tour problem to accommodate intermediate disposal facilities in the context of waste collection

Vera Fischer, Meritxell Pacheco Paneque, Reinhard Bürgy

Door-to-door waste collection comes with a high fuel consumption, emissions and noise. These can be confronted by reducing the number of stops performed by collection vehicles. One possibility consists of locating collection sites throughout the municipality such that residents bring their waste to their most preferred (e.g., closest, most convenient) location. The optimization problem consists of selecting a subset of candidate locations to place the collection sites such that each household disposes the waste at the most preferred location from the chosen ones. The objective is to minimize the total time associated with the distances covered by vehicles to visit the collection sites and the time spent at them. This problem can be seen as a capacitated multi-vehicle covering tour problem. To efficiently solve practical instances, we propose a two-phased heuristic method to address the two subproblems this problem is built on: a set covering problem to select the collection sites and a capacitated vehicle routing problem to determine the routes. Despite the reduction in the number of stops, this strategy does not allow to use smaller collection vehicles (which are more sustainable) because the disposal facility is typically far away. This can be addressed by introducing intermediate disposal facilities within the municipality. The waste is collected by the small vehicles and discharged at the intermediate disposal facilities. A larger vehicle brings the waste from there to the main disposal facility. We are interested in extending the problem to accommodate intermediate disposal facilities. We evaluate how to adapt the developed MILP formulation and heuristic method to this setting and analyze the impact of such a strategy on the overall costs.

4 - A facility location problem for waste collection with minimum workload and penalties

Meritxell Pacheco Paneque, Vera Fischer, Reinhard Bürgy

In most Swiss municipalities, a curbside system consisting of heavy trucks that stop at almost each household is used for non-recoverable waste collection. Due to the many stops of the trucks, this strategy causes high fuel consumption, emissions and noise. These effects can be alleviated by requesting residents to bring their waste to collection facilities comprising large containers that are located in their neighborhood. When a container is full, it is replaced by an empty container that is transported by a truck from the disposal facility (depot) to the collection facility. The truck transports the full container to the disposal facility and discharges it. When designing such a collection system, one main decision consists of selecting the locations for the collection facilities. This optimization problem can be seen as a facility location problem with two particular features. First, for a collection facility to be placed on a candidate location, its collected waste must be greater or equal than a minimum workload that justifies its opening. Second, we assume that residents prioritize candidate locations according to a preference list. This list ranks candidate locations according to the preferences of residents (e.g., walking distance, convenience). The preference list is divided in two parts based on a given threshold on the level of acceptability of locations (e.g., maximum walking distance). Hence, if residents have to use collection facilities that are placed in unacceptable locations, the municipality has to pay a penalty to compensate them. The objective is to minimize the overall cost, which comprises location and penalty costs. We test the resulting formulation on real-life instances and evaluate the trade-off between total cost and resident satisfaction.

■ WC-15

Wednesday, 13:00-14:20 - Silberhorn

GOR PhD thesis awards 2020

Stream: PC Stream
Sponsored session
Chair: *Peter Letmathe*

1 - Matchings and Flows in Hypergraphs

Isabel Beckenbach

The well-known concept of a graph is general enough to model and formulate a lot of mathematical and real world problems and concrete enough to allow for a rich structural and computational theory. However, some real world problems can be formulated more accurately using hypergraphs. For example, in a project of Zuse-Institute-Berlin and Deutsche Bahn regarding optimization of rolling stock rotations several requirement are modelled using directed hyperarcs. This was the starting point of our investigation of hypergraphs. As hypergraphs are a very general mathematical structure we focus on hypergraphs with some additional structures. In this way it is possible to extend several graph theoretical results to hypergraphs. First, I present Hall-type theorems on perfect matchings, perfect f-matchings, and f-factors on several classes of "bipartite" hypergraphs. Afterwards, I consider so called matching-covered hypergraphs, which are hypergraphs in which every hyperedge is contained in a perfect matching. A matching-covered graph has a unique tight-cut decomposition. This is not true for matching-covered hypergraphs, however, it still holds for a special superclass of matching covered, uniform hypergraphs (all hyperedges have the same size). I conclude with results concerning a special class of directed hypergraphs, coming from the rolling stock rotation optimization problem. In this application hyperarcs are a union of standard arcs. Some results on flows in directed graphs can be transferred to flows on these specific directed hypergraphs, e.g., the concept of a residual network or the network simplex algorithm. On the other hand, some properties are lost as for example the integrality of a flow for integral input data.

2 - Optimization and Advanced Analytics to Increase Fairness and Employee Satisfaction

Lena Wolbeck

The digital transformation is revolutionizing the world of work. However, not all occupational groups benefit from flexible new work concepts. Flexibility is particularly limited for employees who work in varying shifts. Shift work has a major impact on work-life balance and circadian rhythm causing negative psychological and physiological effects. Therefore, companies are increasingly spending effort on making schedules socially acceptable. The use of a decision support system for the initial schedule generation as well as for rescheduling in case of disruptions occurring during operations increases the objectivity and reliability of scheduling. Besides minimizing personnel costs, current approaches focus on preference fulfilment. In this context, taking previous planning periods into account is of particular importance in order to compensate any imbalances and to maintain and improve employee satisfaction in the long term. This dissertation examines how optimization methods and advanced analytic techniques contribute to increase fairness and employee satisfaction in shift work. As case studies serve a care facility, two hospitals and a call center, which provide data for evaluation of the artifacts developed. A pattern-based optimization model for scheduling addresses the problem of taking historical data into account. It enables the reduction of extra hours while considering individual preferences. Application of an exact solution approach for the reactive rescheduling indicate that the distribution of short-term shift reassignments is much fairer when previous periods are considered. Computational experiments prove the potential of predictive algorithms to forecast employee absences. As a result, uncertainties are reduced and more robust schedules are generated.

3 - Order fulfillment in e-commerce warehousing: Challenges and solution approaches

Felix Weidinger

Over the last decades, the share of e-commerce sales in the retail sector has grown sustainably. This change in consumer behavior is also forcing changes in retailers' logistical processes. The paradigm shift can be observed particularly well in warehouses, which now no longer have to process large and often regularly scheduled store orders, but rather small, heterogeneous, and also highly time-critical customer orders. Traditional warehousing systems are either only able to meet these requirements with enormous resource input or, in most cases, not at all. This contribution shows what the challenges of modern e-commerce warehousing are and presents new approaches to solve them, either by adapting existing warehousing systems or by using new technologies to develop novel warehousing systems. Special attention is paid to modified processes as well as related planning problems.

4 - Optimal Procurement and Inventory Control in Volatile Commodity Markets - Advances in Stochastic and Data-Driven Optimization

Christian Mandl

Volatile prices constitute a challenge for both commodity-processing and commodity-trading firms. This dissertation investigates the implications of price uncertainty on the optimal operating policies in procurement and inventory control.

A central contribution to the existing literature that addresses the full information problem is the focus on the implications of price model uncertainty, i.e., incomplete information about the underlying price process. Based on advances in stochastic and data-driven optimization, we propose mathematical models for practical decision support and test them on real data. Hence, we give guidance to managers in the digital age on how to use real-time information and Big Data in combination with methods from statistical learning theory (Bayesian learning, machine learning) in an optimization framework in order to improve commodity procurement and inventory management decisions.

The first problem considers operational hedging via inventory control. We show how a Bayesian belief structure can be used to express uncertainty about the price process, which is subject to switches in regimes. We prove the structure of the optimal storage policy and test its cost impact relative to several more practical but suboptimal control policies.

The second problem addresses commodity procurement via forward contracting. We propose a data-driven and machine learning-enabled mixed integer linear programming model that jointly optimizes forecasts and decisions by training optimal purchase signals as functions of features related to the price. Finally, we quantify the performance loss caused by ignoring feature information in procurement.

The third problem considers optimal commodity storage from the perspective of a merchant with buying, storing and reselling opportunities. We propose several data-driven models for storage optimization. Based on empirical data of six major exchange-traded commodities, we find that optimally structured data-driven policies can outperform state-of-the-art reoptimization approaches.

■ WC-16

Wednesday, 13:00-14:20 - Schilthorn

Planning problems with uncertainties

Stream: OR in Engineering
Invited session
Chair: *Tim Müller*

1 - Pooling of contracts for outsourcing problems with two-dimensional asymmetric information

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 paper, we model an outsourcing problem as a specific principal-agent-relationship in which two-dimensional hidden characteristics describe the agent's type. Assuming that the principal knows the joint probability distribution on the type space, a standard solution technique for the resulting contracting problem is stochastic optimization on the set of incentive compatible contract menus from which the agent can choose a single contract according to the take-it-or-leave-it principle, respectively. In practice, however, the contract menu which maximizes the expected utility for the principal generally consists of infinitely many single contracts and cannot be determined analytically for all kinds of probability distributions. To address this issue, we present a novel two-step approach which, in a first step, partitions the rectangular type space into a predefined number of subsets and, in a second step, computes an optimal incentive compatible menu of contracts containing a mutual contract for each subset of pooled types by using quadratic programming. Within our computational study we finally show that our method not solely bypasses the above described solution difficulties but also guarantees small optimality gaps by using only few contracts.

2 - Resilient Network Planning: Static Resilience Optimization of Urban Water Distribution Systems for differing geometries

Imke-Sophie Lorenz, Peter Pelz

The assessment of the minimum availability of critical infrastructures, as which the water distribution system classifies, is of importance in the light of urbanization. Therefore, the concept of resilience is incorporated in the planning and operation process increasingly. Even though the parallelism of urban infrastructures, especially the urban transportation network and the water distribution system, constrains the planning process, there still is a wide variety to master. This is where solving optimization problems assist the planner recently. To include the resilience optimization of these mostly agentless networks, static resilience metrics as graph-theoretical resilience metrics can be applied. These metrics can be represented as constraints or as the objective of the optimization problem. In the present work these two possibilities are studied for graph-theoretical resilience metrics considering the hydraulic resistance of the to be planned or tailored water distribution system. Next to the existing resilience metrics, the total resistance of a network is studied as a suitable and comparable resilience metric to study different urban water distribution systems. Thereby, the scalability of the computational expenses of the metric is of importance. Furthermore, the physical relevance of the scalability of the metric to compare urban water distribution systems of different dimensions is studied to analyze the influence of the geometry of urban structures as a combination of shape and size.

3 - Tracing locally Pareto optimal points by numerical integration

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

We suggest a novel approach for the efficient and reliable approximation of the Pareto front of sufficiently smooth unconstrained biobjective optimization problems. Optimality conditions formulated for weighted sum scalarizations of the problem yield a description of (parts of) the Pareto front as a parametric curve, parameterized by the scalarization parameter (i.e., the weight in the weighted sum scalarization). Its sensitivity w.r.t. parameter variations can be described by an ordinary differential equation (ODE). Starting from an arbitrary initial

Pareto optimal solution, the Pareto front can then be traced by numerical integration. We provide an error analysis based on Lipschitz properties and suggest an explicit Runge-Kutta method for the numerical solution of the ODE. The method is validated on biobjective convex quadratic programming problems for which the exact solution is explicitly known and numerically tested on complex biobjective shape optimization problems involving finite element discretizations of the state equation.

4 - From Design to Operation: Mixed-Integer Model Predictive Control Applied to a Pumping System
Tim Müller, Christoph Knoche, Peter Pelz

The two most significant life cycle phases of products or systems are the design and operation phase. Both share their incredibly high level of complexity due to the available diversity in components, operating settings and interconnection variants. In the design process, two-stage stochastic optimisation problems have proven to be suitable, in which the operation is anticipated by considering various demand scenarios. Since the operation is characterised by uncertainty and fluctuation, subsequently it has to be ensured that the operation is also realised in an optimal way.

In this contribution we show how the original planning problem is transformed into a control problem. For this purpose, the decisions for some of the variable assignments of the planning problem are fixed and thereby the degree of freedom is reduced. The resulting mixed-integer nonlinear problem for the operation represents the model of the system and is solved in two different ways in each time step: On the one hand, the model is used to optimally adapt the model properties to the measured system behaviour, which corresponds to a parameter fitting. This responds to the unavoidable uncertainty in the models. On the other hand, the adjusted model is applied to compute the optimal operating settings for the next time step.

The concept is applied to a pumping system, a pressure booster system for high-rise buildings, and validated on an experimental test-rig.

Wednesday, 14:40-15:40

■ WD-01

Wednesday, 14:40-15:40 - Bundeshaus

SP GOR company award

Stream: PC Stream
Invited session
Chair: *Jens Schulz*
Chair: *Alf Kimms*

■ WD-02

Wednesday, 14:40-15:40 - Zytglogge

SP talk Mansini

Stream: PC Stream
Sponsored session
Chair: *Renata Mansini*

1 - Solving mixed integer linear programming problems by Kernel Search: issues, challenges and future directions
Renata Mansini

A wide range of optimization problems deriving from different application contexts can be formulated as mixed integer linear programming (MILP) problems. The solution of these complex problems is usually addressed with customized heuristic methods that can be seldom reused, even to solve similar problems. In the literature, several attempts have been made to overcome the drawback of problem-dependent heuristics. For example, metaheuristic algorithms introduce general schemes that explore the solution space regardless of the underlying problem structure, whereas general-purpose methods exploit commercial MILP solvers as effective off-the-shelf tools to optimize problems where no specific insight is used beyond the one provided by their mathematical formulations. Kernel Search (KS) can be classified as a general-purpose heuristic framework based upon a straightforward decomposition paradigm. More precisely, KS constructs a sequence of restricted subproblems by identifying a subset of promising variables, called the kernel set, and partitioning the remaining variables into buckets. Each restricted subproblem takes into account the kernel set (possibly updated) plus a selected set of additional variables (the current bucket) and is solved by means of a commercial MILP solver. For this reason, KS is extremely easy to implement. The larger the kernel set, the more likely you are to get better solutions, but also higher computing times. According to the solved problem, KS can consider only a defined number of buckets or scroll the whole sequence of buckets more than once, use disjoint buckets or allow for their partial overlapping, consider equal or variable size buckets. We will discuss the main features and the critical issues of the method by underlining its strong potential and indicating open challenges and future directions. Since the method has produced high-quality solutions for a number of specific (combinatorial) optimization problems, we will also investigate some of its applications providing useful insights for both researchers and practitioners.

■ WD-03

Wednesday, 14:40-15:40 - Münster

SP talk Uetz

Stream: PC Stream
Sponsored session
Chair: *Marc Uetz*

1 - Network Routing and Beyond: Equilibria for Atomic Congestion Games
Marc Uetz

Congestion games are a rich and fundamental class of problems which lie at the core of the area algorithmic game theory, just like the TSP lies in the core of discrete optimization. One well-known example is the result by Roughgarden and Tardos, showing that the price of anarchy in network routing games with affine cost functions equals 4/3. The discrete version of the same problem, where each player chooses a single path instead of routing a flow, has a price of anarchy equal to 5/2. This 5/2 bound holds true for the more general class of atomic congestion games, where players choose arbitrary subsets of resources, while the cost of any resource increases with the number of players using it. There are interesting classes of atomic congestion games, however, which are not yet completely understood. The lecture addresses some open questions, along with some recent results in this context. We specifically consider games with restrictions of players' strategy spaces, but also congestion games where players act sequentially. Some of the results are improvements on the known price of anarchy bounds, but sometimes also also counter-intuitive results where the quality of equilibria deteriorates.

Wednesday, 16:00-17:20

■ WE-04

Wednesday, 16:00-17:20 - Eiger

Scheduling and Network Flows

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Britta Peis*

1 - Convergence of a Packet Routing Model to Flows Over Time

Laura Vargas Koch, Leon Sering, Theresa Ziemke

The mathematical approaches for modeling dynamic traffic can roughly be divided into two categories: discrete packet routing models and continuous flow over time models. We show a connection between the two approaches by formalizing a discrete packet routing model based on the network loading module of the agent-based transport simulation MATSim. For this model, we prove that the limit of the convergence process, when decreasing the packet size and time step length, constitutes a flow over time with multiple commodities. Beside the mathematical convergence proof, we present experiments that indicate a strong connection between the two models. These results increase the relevance of the continuous analytical model and are a theoretical foundation for the simulation software MATSim.

In addition, we show that the convergence result implies the existence of approximate equilibria in the competitive version of the packet routing model. This is of significant interest as exact equilibria, similar to almost all other competitive models, cannot be guaranteed in the multi-commodity setting.

The theoretical part is based on joint work with Sering and Ziemke. The experimental part is based on joint work with Nagel, Sering, Skutella, Ziemke, Zimmer.

2 - Complexity of Source-Sink Monotone 2-Parameter Min Cut

S. Thomas McCormick

There are many applications of max flow with capacities that depend on one or more parameters. Many of these applications fall into the "Source-Sink Monotone" framework, a special case of Topkis' monotonic optimization framework, which implies that the parametric min cuts are nested. When there is a single parameter this implies that the number of distinct min cuts is linear in the number of nodes, which is quite useful for algorithms.

When there are multiple parameters min cuts are still nested, but it was an open question as to how many distinct parametric min cuts could exist. We show that even with only two parameters, the number of distinct min cuts can be exponential in the number of nodes. Despite this negative result, we also show algorithms for solving some typical problems in parametric max flow with multiple parameters.

3 - Assigning and Scheduling Generalized Malleable Jobs

Jannik Matuschke

In malleable scheduling, jobs can be executed simultaneously on multiple machines with the processing time depending on the number of allocated machines. Each job is required to be executed non-preemptively and in unison, i.e., it has to occupy the same time interval on all its allocated machines. In this talk, we discuss a generalization of malleable scheduling, in which a function f(S, j) determines the processing time of job j on machine subset S. Under different discrete concavity assumptions on 1/f(S,j), we show that the scheduling problem can be approximated by a considerably simpler assignment problem and derive LP-based approximation algorithms.

4 - Airplane Refueling, Block-Stacking, and Robust Appointment Scheduling

Simon Gmeiner, Andreas S. Schulz

What is the maximal range of a fleet of aircraft that can share their fuel in flight? What is the largest possible overhang of a stack of blocks? How should tasks whose required processing time can only be estimated be arranged to minimize the costs incurred by deviations from the schedule? The Airplane Refueling Problem, the Block-Stacking Problem, and Robust Appointment Scheduling are three optimization problems with entirely different backgrounds. However, they can all be represented as single-machine scheduling problems with a concave cost function. What is more, the three problems can be polynomially transformed into one another, tying together their (currently unknown) computational complexity and allowing existing algorithms for the Airplane Refueling Problem to be used to solve the other two problems.

■ WE-05

Wednesday, 16:00-17:20 - Mönch

Software for OR - Modeling I

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Linus Schrage*

1 - New Connections to the AMPL Modeling Language: Spreadsheets and Callbacks

Robert Fourer

Optimization applications are often concerned as much with making connections as with building models. This presentation describes two connections recently implemented in the AMPL modeling language and system. A direct spreadsheet connection reads and writes xlsx-format files, defining correspondences between common spreadsheet layouts and AMPL's algebraic data definitions. Support is included for "two-dimensional" spreadsheet tables in which one index labels the columns and one or more indices label the rows. A solver callback connection enables AMPL's APIs to communicate with algorithms as they are running, uniting the ease of modeling in AMPL with the flexibility of programming to customize algorithmic behavior. This facility can be used to write specialized routines that report progress, change settings, and generate constraints that cut off fractional solutions.

2 - New modelling and programming features in Xpress Mosel

Susanne Heipcke, Yves Colombani

The FICO Xpress Mosel software has been turned into free software three years ago in recognition of its increasing use for general programming tasks. In this talk we are going to present examples of recent enhancements and additions to Mosel's functionality that fall under a variety of themes: (1) Mathematical modelling: new modelling constructs have been added for the formulation of non-linear expressions such as absolute/minimum/maximum value, piecewise linear and logical relations that are handled directly by the Xpress MIP solver; secondly, Mosel's matrix handling functionality has been improved, introducing more direct solver access features. (2) Data handling: various extensions to data input for text and database formats have become available, including dataframe-style reading and writing functionality for CSV files. (3) Programming: the Mosel language now supports union types: a union is a container that is capable of holding an object of one of a predefined set of types, e.g. for reading and storing data of a-priori unknown type; furthermore, types such as 'date', 'time', or 'text' can now be used as index sets due to the new possibility of declaring these types as 'constant'. (4) Distributed computing: Mosel provides enhanced support for the implementation of multi-threaded algorithms via cloning of submodels and the possibility of sharing data between cloned models; new coordination mechanisms through remote use of memory pipes and new functionality for monitoring and clearing memory pipes have also been added. (5) Documentation: the moseldoc tool has been extended with features to ease its use on large Mosel projects and Insight apps.

3 - Hardware Considerations for Optimization Software

Ed Klotz, Richard Oberdieck, Kostja Siefen

Gurobi is one of various software libraries that solves optimization problems, but they all need hardware to actually calculate the answers. But what hardware? In this talk we will dive into how optimization problems are being solved on a hardware level, which components of a computer are important and why and finally how you should choose the size of your optimization hardware to get the most out of it. In addition, we will consider how different problem characteristics and algorithms affect the appropriate hardware choice. We will also discuss the differences between the control one has over on-premise machines versus a cloud-based setup, as well as the tools Gurobi offers you to influence the underlying hardware.

4 - Challenges in Interfacing an Optimization Solver with User-Popular Interfaces

Linus Schrage

Many users who might benefit from optimization are accustomed to doing their quantitative work in systems such as Excel, R, Matlab, etc. We describe the approaches we have tried, some successful, some not so, in making optimization available to users in their most comfortable development environment. Some of the challenges faced are: Users do not necessarily formulate their problem in the most optimization friendly fashion. User generated models tend to contain gratuitous nonlinearities, so methods for linearizing, where possible, various nonlinear functions are important. Users in Excel seem to be tempted to use as many as possible of the 300+ functions in Excel. Which are the important ones to recognize and how? Representing uncertainty in models is important. How does one let the user specify: a) the important (typically joint) distributions typically encountered, and b) the sequencing or staging of decisions? Users do not always have a single well-defined objective. How can one best represent problems with multi-criteria? Secondary criteria are particularly important when there are alternative optima, which is frequently the case with integer programs.

■ WE-06

Wednesday, 16:00-17:20 - Jungfrau

Software for OR - MINLP

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Renke Kuhlmann*

1 - The SHOT solver and functionalities for solving convex MINLP problems

Jan Kronqvist, Andreas Lundell

The supporting hyperplane optimization toolkit (SHOT) is an open-source solver based on a polyhedral outer approximation approach, where an equivalent linear or quadratic mixed-integer program (MIP) is dynamically constructed. The solver builds upon the extended supporting hyperplane algorithm (ESH) which was presented in [1], and the solver is described in detail in [2]. In this presentation, we focus on the convex functionalities and algorithms used in the solver. We present a new convex reformulation technique based on eigenvalue decompositions, that results in stronger lifted polyhedral outer approximations. We show that the reformulation significantly improves performance when utilizing linear subproblems. The reformulations also drastically improve performance for convex MIQP and MIQCQP problems when SHOT is used as a fully open-source solver, with CBC and IPOPT as subsolvers.

References [1] Kronqvist, J., Lundell, A. and Westerlund, T., 2016. The extended supporting hyperplane algorithm for convex mixed-integer nonlinear programming. Journal of Global Optimization, 64(2), pp.249-272. [2] Lundell, A., Kronqvist, J. and Westerlund, T., 2018. The supporting hyperplane optimization toolkit—a polyhedral outer approximation based convex MINLP solver utilizing a single branching tree approach. Optimization. Preprint, Optimization Online.

2 - Nonconvex MINLP with the SHOT solver

Andreas Lundell, Jan Kronqvist

The Supporting Hyperplane Optimization Toolkit (SHOT) is a state-of-the-art open-source solver for mixed-integer nonlinear programming (MINLP) problems [1]. It is based on the Extended Supporting Hyperplane (ESH) algorithm, which generates a polyhedral outer approximation of the nonlinear feasible set [2].

In this presentation, we will describe some enhancements from [3] that extend SHOT's capabilities for solving nonconvex problems. The new nonconvex strategies include convexity identification, repair functionality for infeasibilities in the subproblems, and utilizing automated lifting reformulations for special cases of nonconvex terms. Even with these enhancements, SHOT is currently not able to solve general nonconvex MINLP problems with a certificate for globality, i.e., it is still a heuristic solver. But by utilizing automatic convexity detection, SHOT will always return valid bounds on the optimal solution and might even be able to verify the global optimal solution to certain types of nonconvex problems by closing the optimality gap.

References [1] Lundell, A., Kronqvist, J. and Westerlund, T., 2018. The supporting hyperplane optimization toolkit—a polyhedral outer approximation based convex MINLP solver utilizing a single branching tree approach. Optimization. Preprint, Optimization Online.

[2] Kronqvist, J., Lundell, A. and Westerlund, T., 2016. The extended supporting hyperplane algorithm for convex mixed-integer nonlinear programming. Journal of Global Optimization, 64(2), pp.249-272.

[3] Lundell, A., Kronqvist, J., 2021. Polyhedral approximation strategies for nonconvex mixed-integer nonlinear programming in SHOT. Journal of Global Optimization. Available online.

3 - Hyper-optimisation algorithms for MINLP problems

Nikos Kazazakis

We introduce a new class of self-improving algorithms, Hyper-optimisation algorithms, for general MINLP problems.

Hyper-optimisation algorithms utilise information generated when users run optimisation problems. This information is pushed to the Octeract Hyper-optimisation servers, and is used to generate improved algorithms in the background. The end result is that when a user runs the same (or similar) problem again, there is significant improvement in solving speed, sometimes by thousands of times.

These improved algorithms often transcend individual users in utility. The system pushes new algorithmic configurations to a pool that is available to all Hyper-optimisation users, meaning that once a user-submitted problem of particular structure has been algorithmically improved, those improvements become available to all users.

The Hyper-optimisation server uses sophisticated problem classification algorithms, based on Octeract Reformulator technology. These algorithms constantly run in the background to intelligently classify problems that the system determines are similar in terms of exploitable structure.

The Hyper-optimisation system uses a combination of methods, such as machine learning, to proactively generate new algorithms that will solve problems faster. Intuitively, this is a combination of automated tuning as well as re-arranging base algorithmic blocks in order to produce optimal algorithms for given problem structures.

When a user runs a problem, a predictor system is triggered. If the predictor determines that the a new algorithm will work better than default Octeract Engine algorithms, new algorithmic configurations are then received and utilised by the Octeract Engine client, resulting in faster runs in the overwhelming majority of cases.

4 - Spectral relaxations for global optimization of mixed-integer quadratic programs

Nikolaos Sahinidis, Carlos Jose Nohra Khouri, Arvind Raghunathan

We consider the global optimization of mixed-integer quadratic programs. We present convex quadratic relaxations derived by convexifying nonconvex quadratic functions through perturbations of the quadratic matrix. We investigate theoretical properties of these quadratic relaxations and relationships to certain semidefinite programs. We report computational results with the implementation of these relaxations in the solver BARON, demonstrating very significant reductions in BARON's computational times.

■ WE-07

Wednesday, 16:00-17:20 - Niesen

Applications in Traffic

Stream: Mobility and Traffic
Invited session
Chair: *Marcel Dumeier*

1 - Signal Control as a Strategy for Optimizing Large Scale Evacuation - A Review

John Micha Rüpke, Kathrin Fischer

With the number of worldwide disasters steadily growing, also the relevance of relocating large numbers of vulnerable people from threatened to safer areas, better known as large scale evacuation (LSE), increases. In combination with the benefits of modern computational power, this development has resulted in LSE becoming an important application of optimization within the past two decades.

Starting with the formulation of the first rather simple LSE optimization models, either as network-flow or as cell-based models, at the beginning of the century, more and more extensions have been introduced and further developed. These extensions range from adding reality enhancing constraints (such as stochasticity and human behaviour constraints) to implementing evacuation acceleration strategies such as signal control (e.g. traffic light settings, left-turn prohibition or ramp metering) or network re-design (e.g. intersection elimination or contraflow).

In this presentation, a literature review tackling LSE models and extensions will be provided, clustering optimization models enhanced by signal control as an evacuation acceleration strategy by different model specifications as well as by solution methods. Furthermore, an overview of selected models optimizing traffic light timing within an evacuation context will be presented, highlighting their specifics and contributions to the subject.

It will be shown that signal control strategies are an important research field in order to enable the implementation of realistic model conditions while simultaneously providing a means for accelerating total evacuation time. Based on the review, further research options and needs are identified.

2 - ChronoPath - A tool for railway infrastructure modelling and analysis

Julian Reisch, Reyk Weiß, Peter Großmann

Railway infrastructure managers compare and evaluate different version of their infrastructure. For example, long-term infrastructure developments and timetable scenarios, as well as medium- and short-term construction site plannings, are based on potential infrastructure versions. Each version consists of many microscopic-grained properties, such as tracks, stations and signals with specific properties such as electrification or critical load limits. In this paper, we present ChronoPath, a tool that reads infrastructure data, propagates implicitly contained properties, analyses the data for inconsistencies and displays the result with its properties in interactive graphs. We describe the tool's data model and the algorithms for the propagation of implicit data. Furthermore, we provide results on computation times for real-world infrastructure data provided by DB Netz, Germany's largest infrastructure manager.

3 - Computation of Spatiotemporal Travel Times Using Floating Car Data

Lukas Spengler, Marius Madsen, Marc Gennat

Controlling and monitoring traffic flow are key issues to develop and implement sustainable solutions for transportation systems. Therefore, a solid database is inevitable. Large international technology companies like Google or Apple collect a huge amount of data. Unfortunately, these data are not freely available. This is why basic knowledge on traffic flow like spatiotemporal driving speeds is rarely available for municipal traffic planners. This contribution presents a method to compute spatiotemporal average traffic speeds based on floating car data (FCD) coordinates, in one-minute increments using parameter estimation. FCD were collected by a taxi company in Krefeld with 38 vehicles within 2019. Approximately 17 million data points were recorded. To prepare FCD, data points are separated for each trip and cabstand waiting times are filtered. FCD coordinates for each trip are merged with a road network based on OpenStreetMap data, which contains information of the name and type of the street, speed limits and number of lanes for each of 60.000 road sections in Krefeld. Inaccuracies of FCD points, which cannot be unambiguously assigned to a road section, are remedied. The investigated FCD data provides several GPS points within the same minute, thus, these points show the same timestamp. Due to this, the temporal resolution of the pre-processed data has to be refined by estimating the time stamp seconds using Travelling Salesman Problem algorithm. Finally, the average travel time is computed by parameter estimation for every road section a vehicle travelled on. If the quantity of data is sufficient with respect to data point versus street sections, a statement on the diurnal variation of travel speed can be set as well.

4 - A combined electric vehicle charging station location and charging model

Marcel Dumeier, Jutta Geldermann

A growing number of electric vehicles is projected to have a significant impact on the overall electricity demand and the demand variations throughout the day in Germany. The placement and capacity of charging stations influences when charges can be conducted. In a renewable energy system, surplus or insufficient electricity generation may produce incentives to shift charging activities and may therefore have an additional effect on the preferred charging times. Another important factor influencing preferred and available charging locations is the travel profile of individuals throughout the day in cities. To assess these trade-offs between mobility behavior and electricity system, a mixed-integer linear optimization model for capacity and location planning of charging stations is implemented. This model coordinates both, the expansion of the charging infrastructure and charging of vehicles for different electricity system configurations and degrees of vehicle diffusion. To solve the model, exact and heuristic approaches have been implemented and are presented. To assess the performance of the different approaches, the model is applied to a case study for the expansion of the charging infrastructure in a German city. The heuristic approaches make use of the problem characteristics e.g., geographic information and variable energy costs to solve the optimization model and can support decisions on the optimal placement of the charging infrastructure on strategic and operational levels.

■ WE-08

Wednesday, 16:00-17:20 - Stockhorn

Future energy systems - insights from model comparisons

Stream: Energy and Environment
Invited session
Chair: *Michael Bucksteeg*
Chair: *Steffi Misconel*

1 - Model experiments on development pathways for new electricity applications and their impacts on critical electricity supply situations

Steffi Misconel, Dominik Möst

In context of the energy transition, a new energy landscape is emerging in Germany with high shares of renewables, increasing electrification through sector coupling and resulting interactions between several actors, established and new low-carbon technologies. To ensure transparency of energy system analysis and to stimulate continuous model improvement, model experiments and methodologically oriented model comparisons are crucial. The objective of our model experiment is to compare the results of different modeling approaches for the market penetration of new electricity applications and their impact on generation adequacy. The focus is on the market penetration of electric mobility and heat pumps in residential buildings. To analyze the cross-sectoral interdependencies, demand-side models from transport and heating sectors as well as energy demand models are coupled with electricity market models to form a consistent energy model system. The demand-side models simulate future energy demand, market penetration of new electricity applications, and their expected load profiles. The research focus of the electricity market models is on the analysis of the electricity generation side and its impact on the future security of supply. The experiment is divided into the following three-stage model comparison: (i) Direct model comparison - comparison of results from models with similar analysis focus; (ii) System view comparison - model coupling to an energy model system and comparison of results from a system perspective; (iii) Iteration step comparison - multiple iterations to check the results' robustness. The results of the different comparison steps are compared between the individual model approaches and the deviations are analyzed from a methodological point of view.

2 - Phasing out coal - An impact analysis comparing five large-scale electricity market models

Arne Postges, Michael Bucksteeg, Oliver Ruhnau, Eglantine Künle

Motivation Coal is still one of the main energy sources in the electricity sector in several European countries. While coal phase-outs are a straightforward and direct measure to reduce CO2-emissions, the phase-out implementation is subject to ongoing evaluation and discussions. Debates on coal phase-outs are often supported by model-based analyses, but the results and policy implications vary between studies due to varying assumptions and methodologies. However, the impact of different assumptions and methodologies is usually not addressed in these studies and has yet remained unclear.

Methods To address this gap, we perform a systematic comparison of five large-scale electricity market models that are applied to two European scenarios with different coal phase-out strategies. One strategy is based on the age of coal power plants and the other considers economic criteria. To focus on model-related differences in the results an evolved diff-in-diff approach is proposed.

Results Our findings on the three dimensions reliability, efficiency, and environmental compatibility of the power supply expand on those of earlier studies and provide more general takeaways both for modelers and decision makers in the energy industry and policy area. In general, we find that while there is a consensus on how to model the merit-order-based dispatch in electricity markets, this is less the case for technical details such as constraints for combined heat and power production, reserve provision, or ramping constraints. But in the end these details are found to be quite important when analyzing a coal phase-out strategy. Last but not least the performed analysis highlights the pivotal role of the reference scenario for the derived conclusions.

3 - The impact of carbon prices on power sector emissions: insights from a model-comparison experiment

Oliver Ruhnau, Michael Bucksteeg, Arne Postges

The European electricity industry, the largest sector of the world's largest cap-and-trade scheme, is one of the most-studied examples of carbon pricing. Existing analyses often use one individual model to study the development of carbon prices and emissions under a variety of assumptions. In this paper, we study the uncertainty of emissions responding to carbon pricing. While parameter uncertainty is often addressed through sensitivity analyses, potential uncertainty about the models themselves remains unclear. Here, we study model uncertainty by running a structured model comparison experiment, where we expose five numerical power sector models to aligned input parameters - finding stark model differences. At a carbon price of 27 EUR /t, models estimate that European power sector emissions decrease to 400-640 Mt in 2030 (36-58% less than 2016). Most of this variation can be explained by the extent by which models consider market-driven decommissioning of coal- and lignite-fired power plants. Higher carbon prices of 57 and 87 EUR /t yield a further decrease in carbon emissions to 240-540 and to 190-490 Mt, respectively. The higher end of these ranges can be attributed to the short-term fuel switch captured by the dispatch-only models. The lower emissions correspond to models which additionally consider market-based investment in renewables. Further studying country-specific differences, we identify the representation of combined heat and power as another crucial driver of differences across models.

4 - Possibilities to assess climate uncertainty in the planning of energy systems - a case study on hydro power in southwest Europe

Leonie Sara Plaga, Valentin Bertsch

Energy system analysis is a powerful tool to support the planning of future energy systems. Especially when looking into systems with a high share of renewable energy, different climate and weather conditions can significantly influence the model outcome. But the future climate is still subject to large uncertainties. Thus, there are many different climate models with different projections. Today, it is unclear which model will be closest to the future reality, but investment decisions must still be made. Therefore, energy system models which assess projections from multiple climate models are necessary. Here, different objectives can be applied: Is the aim to find the solution, which is optimal for the majority of models or the solution which still performs adequately in the worst case? Furthermore, due to the high number of climate models and scenarios, data analysis is necessary to reduce computation time. In this study, a case study is performed on the energy system of southwest Europe. The output of the energy system model is compared when using different methods to incorporate data from three different climate models for river runoff. As a reference case, the total system costs are minimized using the complete river runoff data from all three models as model input. In a second case, it is shown, that using synthetic datasets created by Markov Chains can reduce computation time compared to the reference case, but leads to a cost increase of 4.8% compared to modelling with complete information. In the third case, the solution for the system is found by minimizing the maximum regret instead of the total costs. The regret for two of the three climate models is reduced compared to the reference case, but the total difference to the reference case is only 0.03%.

■ WE-09

Wednesday, 16:00-17:20 - Gantrisch

Dynamic Decision Problems

Stream: Systems Modeling and Simulation
Invited session
Chair: *Maximilian Moll*
Chair: *Andrea Emilio Rizzoli*

1 - On the Matthew effect in research careers
Andrea Seidl, Gustav Feichtinger, Dieter Grass, Peter M. Kort

The observation that a socioeconomic agent with a high reputation gets a disproportionately higher recognition for the same work than an agent with lower reputation is typical in career development and wealth. This phenomenon, which is known as Matthew effect in the literature, leads to an increasing inequality over time. The present paper employs an optimal control model to study the implications of the Matthew effect on the optimal investments of a scientist into reputation.

The solution of the model exhibits, for sufficiently low effort costs, a steady state that serves as a threshold level separating success and failure in academia. We find that at this steady state the solution can be abnormal. We discuss reasons for the occurrence of abnormality and show that abnormality can be an integral part of a meaningful problem rather than to be a sign of degeneracy.

2 - Routing in Reinforcement Learning Markov Chains
Maximilian Moll, Dominic Weller

With computers beating human players in challenging games like Chess, Go, and StarCraft, Reinforcement Learning has gained much attention recently. The growing field of this data-driven approach to control theory has produced various promising algorithms that combine simulation for data generation, optimization, and often bootstrapping. However, underneath each of those lies the assumption that the problem can be cast as a Markov Decision Process, which extends the usual Markov Chain by assigning controls and resulting rewards to each potential transition. This assumption implies that the underlying Markov Chain and the reward, the data equivalent of an inverse cost function, form a weighted network. Consequently, the optimization problem in Reinforcement Learning can be translated to a routing problem in such possibly immense and largely unknown networks. This paper analyzes this novel interpretation and provides some first approaches to its solution.

3 - Resource Optimization in Mass Casualty Management: A Comparison of Methods
Marian Sorin Nistor, Maximilian Moll, Truong Son Pham, Stefan Wolfgang Pickl, Dieter Budde

The Emergency Medical Services resources, such as vehicles and personnel, are often challenged in mass casualty incidents. A triage area is created in severe cases at every location, and an incident commander is appointed to manage the available resources. To respond swiftly and optimally in such situations, this paper studies and compares various optimization approaches ranging from classical optimization to machine learning. Key points of interest in the comparison are the solution quality and the speed of finding it. In multiple-casualty scenarios knowing both is essential to choosing the correct method. Two realistic case studies of different sizes are being considered here to give an indication of scalability. One is a natural hazard, a flood around the Costesti-Stanca Reservoir Lake on Prut River in the Republic of Moldova. Here, the forecasting and the pre-allocation of resources are expected from multiple hospitals from the region for a large number of victim requests coming from three affected villages. The second scenario is a human-made disaster, a fire outbreak in the outskirts of Floresti city, Republic of Moldova. The number of victims is reduced, but the fatality rate is highly increased. Both scenarios aim to mitigate the fatality rate by optimizing the number of victims receiving specialized treatment at the nearest available hospital with the required profile, e.g., traumatology, pneumology, or surgery.

4 - Worker cross training impact on service level of an electronics manufacturer - simulation-based optimization for a real world case
Andreas Schober, Victoria Lausberger, Klaus Altendorfer, Andreas Beham

To react on customer demand uncertainty, production systems have to be flexible concerning the provided capacity. Worker cross training is, therefore, an important aspect in providing short-term capacity adjustments to fulfil customer demands and meet respective due dates, as workforce can be shifted between stations, leading to additional flexibility in available capacity. Therefore, the objective of this study is to optimize workforce qualifications and cross training patterns of an electronics manufacturer, i.e. a real world case, whereby service level is maximized and overall number of skills is minimized. A holistic simulation model of the real world multi-stage production system is created, including 2639 unique materials, 71 workstations and machines, 37 specific qualifications and 58 employees. A heuristic for stochastic worker absence, based on the real absence distribution, is applied to consider absence times like vacation and sick leave. A bi-objective simulation-based optimization is applied to optimize the skills of the employees. The results are compared with a set of qualification matrices identified by experts. Results show that the predefined qualification matrices, stated by experts, are by far outperformed by the simulation-based optimization. Another constraint (originated from experts' input) is, that employees should be divided into skill groups and their number should be kept small. Therefore, the simulation-based optimization is extended by a third objective, i.e. minimize number of skill groups. Simulation-based optimization is shown to perform well for this huge space of optimization parameter and respective results show a significant increase in overall skills (for same service levels) when number of skill groups are minimized.

■ WE-10

Wednesday, 16:00-17:20 - Schreckhorn

City Logistics

Stream: Logistics and Freight Transportation
Invited session
Chair: *Christian Tilk*

1 - Optimizing combined truck and cargo bike tours for last-mile deliveries
Moritz Stinzendörfer, Philine Schiewe

There are many concepts for optimizing last-mile logistics to deliver goods as fast and cheaply as possible to their new owner. In addition to time and cost, nowadays the environmental aspect also plays a major role. To reduce air pollution and traffic in urban areas, new ways of transportation are needed to be designed and implemented. Instead of a futuristic drone approach, we focus on two already established means of transport, the truck and cargo bike. While it is reasonable to assume that the capacity of the truck is sufficiently large to transport all goods to be delivered at once, the bike capacity is limited. This results in a hybrid model of a truck, starting and ending at a depot with all goods, and a cargo bike that has to be resupplied during the delivery route. Opposed to solving a two-step problem, where bike depots are installed and stocked separately, we are considering an integrated approach without further infrastructure needs. We present a new variant of the TSP, where the truck both delivers goods and serves as a moving mini-depot for the cargo bike, resulting in challenging synchronization and load constraints. We model this problem as an IP in various versions, minimizing delivery time, distance, or emissions, and prove upper bounds compared to the truck-only delivery. Furthermore, we show worst-case approximation ratios for modified heuristics of known problems and develop several new ones, based on route first - cluster second approaches or prioritizing one of the transport modes. In our experimental study, we analyze the performance of our heuristics and show the advantages of our approach compared to fixed depots. Moreover, we extend this problem to include multiple bikes and apply modified heuristics for the vehicle routing problem.

2 - An optimization-based comparison of different distribution systems in City Logistics
Barbara Himstedt, Frank Meisel

Making the last mile more efficient and environmentally friendly is one of the major challenges in city logistics. Not least because conventional delivery with diesel vans is no longer desirable in many cases. In recent years, great efforts have therefore been made to research and implement alternative delivery concepts, such as delivery by cargo bikes, drones or autonomous delivery robots. However, these approaches usually relate to the use of only one of these distribution systems at a time. Our aim is to combine them and find out how they can complement each other and which ones should be considered more substitutive. To this end, we developed a MILP Model that modularly links several distribution concepts. The basic setting of this model includes a depot on the outskirts of a city, from which a smaller depot in the city centre can be supplied and at which smaller, eco-friendly delivery vehicles are stationed. In a first variant, deliveries are made by larger vans and cargo bikes. In addition, there is the option to drop off boxes by van, serving as mobile hubs to supply the low-capacitated bikes with goods en route. A second variant does not use the vans to deliver to customers at all but only for supplying the inner city depot and to place the boxes. The final delivery of the goods is then carried out with by cargo bikes and small autonomous robots. These variants, as well as modifications of other fleet combinations are investigated by computational experiments in terms of performance, efficiency, and environmental friendliness. Thereby we not only consider different cost structures, but also investigate the impact of different customer densities or varying levels of individual customer demands on the performance of the respective distribution concepts.

3 - Using public transport systems in last-mile deliveries
Jeanette Schmidt, Christian Tilk, Stefan Irnich

In this talk, we consider a 2-Echelon Vehicle Routing Problem that integrates public transport systems into classical freight flows for last-mile deliveries. In particular, we make use of the free capacity of an already established public transport system that operates according to predetermined routes and schedules to bring goods from outside of the city into the city. The problem aims at routing a given set of vehicles to pick up the goods from a set of scheduled-line stops and deliver them to the final customers.

To solve the problem, we present a branch-price-and-cut (BPC) algorithm. The resulting pricing problem is a shortest-path problem with resource constraints that is solved with a bidirectional labeling algorithm on an auxiliary network. We present optimal solutions for instances with up to 75 customers. Moreover, we tackle larger instances with a heuristic version of the BPC and give some managerial insides.

4 - A matheuristic for a two-echelon vehicle routing problem with satellite capacities and reverse flows
Christian Tilk, Dorian Dumez, Stefan Irnich, Fabien Lehuédé, Katharina Olkis, Olivier Péton

In two-echelon vehicle routing problems, customers are supplied from distribution centers through intermediary satellites. First-echelon vehicles transport goods to satellites, at which second-echelon vehicles collect the goods and deliver them to the customers. The flow of goods must respect operational and load synchronization constraints, i.e., one must decide on the assignment of each customer to a satellite and ensure that incoming and outgoing quantities at each satellite coincide. We extend the basic version by integrating reverse flows and satellite capacities which introduce several additional synchronization issues. To solve the arising problem, we employ a matheuristic solution approach that is based on different decompositions of the overall problem. We evaluate the performance of our algorithm on instances for special cases of our problem that are already discussed in the literature and present computational studies focusing on the impact of reverse flows and satellite capacities.

■ WE-11

Wednesday, 16:00-17:20 - Wildstrubel

Financial Modelling II

Stream: Finance
Invited session
Chair: *Florian Pauer*

1 - Barrier Option Pricing With Trading and Non-Trading Hours
Philip Rosenthal, Rainer Baule, David Shkel

Continuously monitored barrier options are common components of derivative retail structured products. Because barriers can only be breached during trading hours, traditional pricing formulas severely overestimate the barrier hit probability and consequently underestimate the option value, especially if the underlying is close to the barrier. While it is possible to integrate non-trading hours in a Monte Carlo simulation to calculate prices, market makers need to continuously quote prices for thousands of products. Consequently, computational speed can be an issue.

We introduce a semi-analytical pricing approach, which takes non-trading hours into account. With this approach, we are able to analyze the behavior of down-and-out put option prices throughout the trading day and find a common pattern across different market conditions. Given a small and constant distance to the barrier, prices of down-and-out puts tend to rise over the trading day, with a steep increase close to the end of the trading day. This can be linked to the barrier hit probability, which is adequately captured in the proposed valuation approach, but is overestimated in classical pricing formulas.

2 - Time-to-Build and Capacity Expansion
Haejun Jeon

We study a firm's optimal investment timing and capacity decisions in the presence of uncertain time-to-build. Because of the time-to-build, the firm can expand its capacity before or after the initial project is completed, and learning by doing enables that the lags of the follow-up investment can be shorter than those of the initial project. We derive the optimal investment strategies in each scenario and examine the impact of time-to-build on the investment dynamics. We show that both the initial and the follow-up investment can be made earlier in the presence of time-to-build than they would in the absence of the lags, especially in a volatile market. This is in contrast to the case of a single investment, whose timing is always delayed by the time-to-build. Furthermore, the capacity of the follow-up project dominates that of the initial one in the presence of time-to-build, whereas the latter dominates the former in the absence of the lags. The capacity choice of each project, however, is non-monotone with respect to the size of the lags. We can endogenize the degree of learning by doing based on the proportion of capacity in each stage of the investment. Endogenous learning by doing is found to be non-monotone with respect to the size of the initial lags because the learning incurs costs of more investment at the earlier stage.

3 - Sell or Hold? On the Value of Non-Performing Loans and Mandatory Write-Off Rules
Florian Pauer, Stefan Pichler

In this paper, we study the impact of mandatory write-off rules on a bank's reservation price of a non-performing loan (NPL). We develop a model of information asymmetry in NPL markets where agents are using risk neutral pricing. In contrast to the existing literature, we assume that agents agree on the expected recovery rate of an NPL. We show that differences in the estimation accuracy of the drift of the underlying recovery rate process lead to valuation differences. In the model, the differences in the precision when estimating the drift of the underlying lead to differences in the aggregated variance of the payoff distribution. Since an NPL's payoff function is nonlinear this results in different NPL valuations depending on this precision parameter. This, in combination with capital adequacy requirements banks need to maintain and funding costs they face leads to the result that a bank's reservation price of an NPL might be below its own valuation.

■ WE-12

Wednesday, 16:00-17:20 - Faulhorn

Applications in Public Transport

Stream: Mobility and Traffic
Invited session
Chair: *Nicki Lena Kämpf*

1 - Computation of Travel Purpose Distribution Using Open Data Sources

Marius Madsen, Lukas Spengler, Marc Gennat

The German government wants to reduce greenhouse gas emissions by 55 percent by 2030 compared to 1990. So far, the transport sector has not been able to reduce its CO2 emissions. A part of the required CO2 emissions savings can be achieved by a modal shift from private to public transport. In order to expand public transportation in a cost efficient way, it is necessary to know the demand and its origin and destination. This contribution shows the computation of a detailed travel purpose distribution model of an average German city using freely available data. A mobility survey serves as a basis, which shows, among other data, how many working day trips are made between city districts. In addition, an hourly average trip purpose distribution is determined. Using data from the free accessible real estate cadastre of the exemplary city, it is possible to determine how many buildings of a specific type of use exist in which city districts. For this purpose, 253 different types of use (e.g. "dormitory") are combined into seven simplified types of use (e.g. "residential"). Mixed- usage buildings are divided among the different simplified usage types as a first approximation. Parameter estimation can be used to compute the district-to-district specific trip purposes by linking the usage type to the associated trip purpose. The third step is to subdivide the city into a 400x400-meter grid and allocate the trip purposes to individual grid point relations. The cadastral data are used to weight the grid points. This results in a 794x794x24 spatiotemporal origin-destination-time-matrix, from which the quantity of routes and its route purpose distribution can be read out. The potential for a demand-oriented public transport expansion can now be determined in further research.

2 - Modeling and Optimizing Fare Systems

Reena Urban, Anita Schöbel

When designing fare systems, often reference prices are given and the goal is to determine new prices such that the absolute deviation between the new and the reference prices is minimized. The so computed fare systems are not always consistent in the sense that it might be beneficial to buy several tickets for a journey or a ticket for an elongated journey in order to save money. We analyze (distance- and zone-based) fare systems with regard to these properties which are called the no-stopover and no-elongation property. Furthermore, these properties help to deal with the cheapest ticket problem, i.e., finding a cheapest ticket to travel between a pair of stations. Passengers would like to minimize their ticket prices as one among other criteria when planning their journeys. Also public transport companies can determine a lower bound on their income when knowing cheapest ticket prices for the demand. The complexity and the algorithmic approach to solve the cheapest ticket problem depend crucially on the underlying fare system. These analyses yield additional information about fare systems which we utilize to improve the design of fare systems. We present integer programming formulations of the tariff design problem for different fare systems which include new constraints for desirable properties, e.g., constraints ensuring the no-stopover and the no-elongation property making the fare systems more consistent.

3 - Automatic generation of a service intention in public transport with integrated travel chains

Stephan Buetikofer, Raimond Wüst, Joël Köchli

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 example.

4 - Bayesian Optimization for Neural Networks with Small Sample Size Data: A Combined Approach for Feature Selection and Hyperparameter Tuning

Nicki Lena Kämpf, Sandra Spiegelberg, Jonas Krembsler, Nicola Winter, Thomas Winter, Robert Knappe

With the rise of Artificial Intelligence, the research in time series forecasting with Neural Networks is growing as well. However, there is a large gap between scientific research and the algorithms used in the private sector. This gap is mainly caused by two problems: 1) the scientific studies mostly rely on large sample size data sets which are not available in practice and 2) the scientific papers seldomly focus on the importance of the feature selection. To narrow the gap between scientific research and the application of Neural Networks, this paper proposes a combined approach for feature selection and hyperparameter tuning with Bayesian Optimization. This combined approach allows for a generalizable, end-to-end training and optimization of Deep Neural Networks. Using a combined approach reduces the problems of overfitting and high-variance gradients for high dimensional, small sample size data sets. The advantages are demonstrated for a real-world revenue data set with a small sample size. The results will be used in a research project in the field of public transportation. The goal is to automate the revenue controlling and implement data-driven decision-making in the existing controlling processes.

■ WE-13

Wednesday, 16:00-17:20 - Blüemlisalp

Behavioral Operations and Risk

Stream: Game Theory and Behavioral Management
Invited session
Chair: *Stefan Haeussler*

1 - Classification in the Wild: The Science and Art of Transparent Decision Making

Konstantinos Katsikopoulos

"In the wild" refers to situations where, unlike in a typical psychological experiment or decision model, uncertainty cannot be meaningfully reduced to probability. Jimmie Savage, father of modern Bayesian decision theory, argued that even planning a picnic lies outside it. Can decision making in the wild be based on science? Yes. We introduce formal models, often absent in psychology. Machine learning has formal models, such as neural networks and random forests, which can be effective in the wild but are not transparent. When systems based on these tools are used in financing or in courts, it remains a mystery to loan applicants or defendants why they were denied the loan or bail. Classification in the Wild is committed to increasing transparency. It provides tools easy to understand, teach and execute. The tools allow practitioners to make fast and accurate classifications when no fancy algorithm is at hand as at the site of an accident or a suicide attack. Classification in the Wild introduces heuristics that are both descriptive and prescriptive, describing the art of how experienced practitioners decide while also systematically studying how to improve it. These heuristics are models of bounded rationality, a term coined by Herbert Simon, founder of artificial intelligence and pioneer of the cognitive revolution. They are useful additions to existing models in psychology and AI, allowing for fast, transparent, and accurate decisions. In the wild, simplicity and transparency are not necessarily enemies of accuracy.

2 - Consumer behavior towards different carbon footprint reductions

Nils Roemer, Guido Voigt, Gilvan C. Souza, Christian Tröster

Recently, the issue of carbon emissions reduction has been gaining strong momentum at both a corporate and governmental level. Companies of the old economy (for example Shell, Daimler or ArcelorMittal) as well as representatives of the new economy (for example Amazon, Apple and Microsoft) publicly declare becoming carbon neutral, or "net zero", as an important goal for their future. They are responding to the demand for sustainable products and services that has been growing in many societies. Companies have a variety of options for carbon emission reductions available to them, such as buying offsets or switching to renewable energy. This raises the question of whether consumers perceive the different types of carbon emission reductions as equivalent, or whether they favor the implementation of certain measures. We investigate this issue empirically through surveys and incentive-compatible discrete choice experiments.

3 - Flow Allocation Games in Financial Networks
Daniel Schmand, Nils Bertschinger, Martin Hoefer

We analyze a game-theoretic version of the maximum circulation problem motivated by applications in financial networks. Every node in a directed network is owned by a separate rational agent. An agent has the incentive to maximize the amount of total flow going through her node. The agent can strategically allocate incoming flow to outgoing edges. We study the existence and computational complexity of pure Nash and strong equilibria, and we provide bounds on the (strong) prices of anarchy and stability.

In the context of financial networks, our model builds upon the seminal work on systemic risk by Eisenberg and Noe. Our game can be used to model strategic incentives to allocate payments in order to clear as much debt as possible. The results highlight the power of regulation – if a central authority can suggest suitable payments, a socially optimal strong equilibrium can be found in polynomial time.

■ WE-14

Wednesday, 16:00-17:20 - Wetterhorn

MCDA in Production and Energy Management

Stream: Decision Analysis and Support
Invited session
Chair: *Fabian Leuthold*

1 - Towards a complex investment evaluation framework for renewable energy systems: A 2-level heuristic approach
David Olave-Rojas, Eduardo Álvarez-Miranda

Renewable energy technologies still endure critical technical and financial challenges. These challenges demand specially tailored decision support tools for planning the (renewable-based) strategical expansion of power systems. However, existing tools not always adequately integrate the tactical and operational dimensions of power systems into the evaluation process; hence, the designed investment strategies might fail to foresee how new infrastructure integrates with the existing power system and also fail to capture the volatile energy market dynamics. In this paper, this methodological gap is addressed by presenting a decision aid framework, based on mixed-integer programming, for supporting long-term decision-making when planning (the expansion of existing) energy systems. The proposed framework relies on heuristically solving an optimization problem coined as the Generation, transmission, and storage location and sizing of operation-aware sustainable power system design problem, which encodes two nested problems: a novel strategic renewable power system expansion problem, and a Unit Commitment problem. Using a case study from the Chilean power system, it is shown that the proposed tool ensures a more realistic and accurate economic evaluation, as it takes into account the influence of the evaluated project on the grid where it will be installed. In the considered case study, we show the impact of renewable sources and energy storage systems on the market operation. Furthermore, the proposed approach is used to investigate how high (public) subsidies on renewable technologies should be in order to increase the penetration of these technologies.

2 - Supporting complex decision-making in multiple criteria-based projects with MCDA-MSS
Marco Cinelli, Milosz Kadzinski, Peter Burgherr, Roman Slowinski

We present the Multiple Criteria Decision Analysis Methods Selection Software (MCDA-MSS), which is the most comprehensive software for recommending MCDA methods. This software contributes to the meta-decision-making problem caused by the very large number of MCDA methods available nowadays, being the decision of which MCDA method(s) to use for a certain decision-making problem. MCDA-MSS provides systematic guidance of an analyst facing this challenge. During the presentation, we will discuss the main characteristics and steps of MCDA-MSS, including the following features. First, it allows analysts to learn our sequential and dynamic framework permitting to describe complex decision-making problems. Second, it comprises the most comprehensive database of over 200 MCDA methods characterized from all relevant points of view. Third, it recommends solutions to those case studies for which no method matches all the requirements coming from the analyst. Fourth, it offers a strategy to reduce a large set of suitable MCDA methods when there is a lot of uncertainty in the description of the decision-making problem. Fifth, it identifies potential errors in MCDA method selection and provides methods that are more suitable. The application of MCDA-MSS will be demonstrated on a set of case studies from the energy systems analysis literature. Notable findings of this testing include discoveries of the use of some weighting methods (e.g., Analytical Hierarchy Process) in MCDA methods not suited for this type of weights, sub-optimal selection of MCDA methods for certain types of problem statements, and lack of handling rather evident interactions in preference models.

3 - A data-driven methodology for the automated configuration of online algorithms
Fabian Dunke

With the goal of devising algorithms for decision support in operational tasks, we introduce a new methodology for the automated configuration of algorithms for combinatorial online optimization problems. The procedure draws upon available instance data and is capable of recognizing data patterns which prove beneficial to the overall outcome. Since online optimization requires repetitive decision making without complete future information, no online algorithm can be optimal for every instance and it is reasonable to restrict attention to rule-based algorithms. We consider such algorithms in the form of procedures which derive their decisions using a threshold value. Threshold values are computed by evaluating a mathematical term (threshold value expression) composed of the available instance data elements. The goal then consists of determining the structure of the threshold value expression leading to the best algorithm performance. To this end, we employ a simulated annealing scheme returning the most favorable term composition given the available instance data. The resulting methodology can be implemented as part of data-driven decision support systems in order to facilitate knowledge-based decision making. Decision rules are generated in an automated fashion once historical input data is provided. The methodology is successfully instantiated in a series of computational experiments for three classes of combinatorial online optimization problems (scheduling, packing, lot sizing). Results show that automatically configured online algorithms are even capable of outperforming well-known online algorithms in respective problem settings. We attribute this effect to the methodology's capability of integrating instance data into the process of algorithm configuration.

4 - A Decision Support System to Optimize Production Quantities during Product Phase-Outs
Fabian Leuthold, Katrin Hügel, Oliver Mörl, Harold Tiemessen

The increasing pressure to innovate lead to ever shorter product life cycles. Manufacturing companies are therefore increasingly faced with the planning of product phase-outs.

One of the big challenges in planning product phase-outs is to determine the number of items of the discontinued product to manufacture in this phase. A common approach to face this challenge is to derive a distribution for the remaining demand for the discontinued product and apply a suitable Last Time Buy model.

However, especially in the B2B environment for capital goods, the remaining demand of the discontinued product can be controlled within a certain range. Consequently, minimizing the scrapping costs of remaining stocks of product-specific components becomes crucial for optimization. Scrapping costs of product families can easily amount to several 100'000 EUR.

We developed a Decision Support System (DSS) to optimize production quantities with respect to scrapping costs, taking into account used-defined maximum sales volumes. The production quantity of the phase-out is usually defined in a negotiation process between sales, production and procurement. Therefore, the DSS must be able to be used live at meetings.

The actual optimization task was formulated as a MIP and solved using a commercial solver. The necessary input data is prepared and imported from the ERP system. Users of the DSS can define and adjust minimum and maximum sales volumes and solve the corresponding MIP within a few seconds.

Experiments with the developed DSS on real-life data from a large international company in the surveying industry show that costs of product phase-outs can be reduced by 20 - 30%.

■ WE-15

Wednesday, 16:00-17:20 - Silberhorn

Machine scheduling

Stream: Project Management and Scheduling
Invited session
Chair: *Julia Lange*

1 - Scheduling a two stage proportionate flexible flow shop with dedicated machines and no buffers

Christian Weiß, Lena Schwehm, Heiner Ackermann

We study a job shop problem motivated by an application in the process industry. Consider a batch chemical plant consisting of one common preparation reactor, called master reactor, which feeds a number of independent production lines. Each production line is designed to produce one distinct type of product, after receiving the required individual starting mixture from the master reactor. For each product type, a given number of batches should be produced as fast as possible. The processing times in the master reactor and the production lines are not dependent on the individual batches, but only on the product type which is processed.

Motivated by this set up, we consider the following job shop problem with two stages. The first stage consists of a single, common machine, corresponding to the master reactor, while the second stage consists of a number of dedicated machines, each of them corresponding to one production line. Jobs are partitioned into job types, one type for each machine at the second stage. Each job is first processed by the single machine at stage one, before continuing onto the dedicated machine at stage two, which corresponds to its job type. Processing times are only dependent on the job types, not on individual jobs. The goal is to finish the necessary jobs as fast as possible, i.e. minimize the makespan.

We show that the problem is strongly NP-hard if the number of job types (or, equivalently, machines at stage two) is part of the input. Subsequently, we discuss different solution methods, including MIPs, approximation algorithms, heuristics, and dedicated exact algorithms for instances with only two or three job types. We also briefly talk about how the problem was solved in practice.

2 - Interval scheduling with resource adjacency considerations

Michael Dienstknecht, Dirk Briskorn

In our research, we consider the problem of 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 which is 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 installation, i.e. a cluster of containers on the construction site. Due to efficiency considerations it is desirable to not disperse trades all over the installation, but to build trade clusters instead, i.e. clusters of adjacent containers with the same trade assigned. We address the problem of assigning trades with given container requirements to containers in a given installation. In doing so, we have to account for different container types and limited container availability times. It is our goal to find a feasible assignment of trades to containers that minimizes the total number of trade clusters. We provide different MIP formulations and develop a decomposition approach for solving the problem.

3 - Decomposition approach for integrated production and maintenance scheduling of parallel machines

Sven Pries, Celso Gustavo Stall Sikora

In modern industrial manufacturing, the high availability of production capacities is as important as it has never been before. To preserve it and hedge against delays due to random failure, preventive maintenance activities are needed which restore the machine's condition but blocking it for production. Thus, the maintenance times are traded off against the delays caused by failures. This is incorporated into an identical parallel machine scheduling problem minimizing the expected makespan.

The problem presented can be decomposed in multiple ways to accelerate the solution process. The assignment of jobs to the intervals between two consecutive preventive maintenance activities at every individual machine can be efficiently solved using a Dantzig-Wolfe decomposition and a branch-and-price algorithm. For, the assignment of jobs to machines, a Benders' decomposition can be used utilizing the lower bound information of the first approach and combining it with combinatorial cuts. Computational results as well as further ideas to improve the performance are discussed.

4 - Scheduling heating tasks on parallel furnaces with setup times and conflicts

Julia Lange, Philipp Fath, David Sayah

Heating and reheating processes constitute time-consuming and costly manufacturing steps in metalworking industries. Therefore, a precise modeling of the real-world restrictions involved and an efficient scheduling of these tasks is of significant importance. The resulting planning problems become especially challenging due to the use of furnaces with different characteristics and interdependencies, distinct product properties and a set of performance indicators which are difficult to measure. Considering a real-world issue, a mathematical formulation for a scheduling problem on unrelated parallel machines with job families, sequence-dependent setup times and job conflicts is presented. The minimization of the total completion time is chosen as the best fitting objective function. The mathematical model is enhanced by different types of valid inequalities also involving a discussion on special symmetry structures appearing for parallel furnaces. A computational study is reported comparing different variants of the model in terms of solution quality, computation time and solvable instance size. The results support the applicability of the proposed mixed-integer programming formulation and point in promising directions for the development of matheuristic approaches to tackle large-scale instances.

■ WE-16

Wednesday, 16:00-17:20 - Schilthorn

Operating Rooms

Stream: Health Care Management
Invited session
Chair: *Katja Schimmelpfeng*

1 - Leveling ICU Bed Occupancy Using a Quota System: An Applied Heuristic for Operating Theater Managers

Steffen Heider

The operating theater as well as the intensive care unit are both one of the most expensive departments within a hospital but also one of the largest revenue drivers. Extensive planning on multiple strategic levels is necessary, to guarantee patient safety, workload leveling as well as profitability of a hospital. Patients are scheduled for each department individually but also jointly across departments when resources are shared. In research, there are many papers that focus on optimizing the utilization of each department individually but also on the patient flow from one department to the other. However, few papers focus on the development of scheduling heuristics that can be used by operating theater managers without knowledge in mathematical optimization. We present an operating theater quota system for elective intensive care patients that minimizes the expected maximum bed demand on the intensive care unit. We develop a heuristic that can be easily understood and applied by operating theater managers. We use multiple instances to show that the heuristic can achieve near optimal results by comparing the heuristic with an optimal approach.

2 - Designing and Evaluating Modified Block Surgery Schedules

Beria Durdevic

The basic concept of master surgery schedules, namely the idea of medical specialties possessing and administering their own weekly surgery time slots and not releasing unused time to others, makes it a rigid scheduling approach that is triggering OR utilization minuses and giving rise to doubts about its practical usefulness. Next to this so-called block scheduling, there is the flexible, opposing method of open scheduling. It entirely dismisses the concept of time slot assignments and instead keeps the weekly schedule open for surgeons to arbitrarily plan their surgeries according to the FCFS rule. However, open scheduling has be found to be benefiting only specialties that are able to plan far in advance and disadvantageous for specialties with not easily foreseeable surgery demand. A promising intermediate solution is modified block scheduling that combines both blocked and open time slots and consequently exhibits the advantages of both the other approaches. The aim of this work is the development of a model that creates these modified block schedules in order to enhance flexibility and maximize utilization whilst providing a satisfactory solution to surgeons who are reliant on fixed time slots and to those who are capable of taking advantage of greater planning flexibility by a partially open schedule. The tactical planning model is designed as to provide schedules that are optimal not solely in terms of the OR utilization but also with regard to a leveled bed occupancy rate. Additionally, a simulation study is conducted to test the operational robustness of the analytically developed schedule. The analytical and the simulation model are supposed to provide a framework for hospital managers for deciding upon the realization of more flexible surgery schedules.

Wednesday, 17:30-18:30

■ WF-01

Wednesday, 17:30-18:30 - Bundeshaus

Meet the Editors

Stream: PC Stream
Sponsored session
Chair: *Norbert Trautmann*

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 Ulrike Leopold-Wildburger from Central European Journal of Operations Research, Oliver Stein from Mathematical Methods of Operations Research and Guido Voigt from OR Spectrum. The editors share insights on the aim and scope of their journals and talk in detail about the review processes. The event is rounded off by a Q&A session on the social platform Gather Town starting at 18:00.

Thursday, 9:00-10:20

■ TA-04

Thursday, 9:00-10:20 - Eiger

Acyclic clorings of digraphs

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Winfried Hochstättler*

1 - Counting acyclic colorings
Johanna Wiehe, Winfried Hochstättler

The notion of classic graph coloring deals with finding the smallest integer k such that the vertices of an undirected graph can be colored with k colors, where no two adjacent vertices share the same color. The chromatic polynomial counts those proper colorings a graph admits, subject to the number of colors. Tutte developed a dual concept, so-called nowhere-zero flows (NZ-flows), which build a polynomial, the flow polynomial, too. Regarding directed graphs, or digraphs for short, the dichromatic number is a natural generalization of the chromatic number. It was introduced by Neumann-Lara in 1982 as the smallest integer k such that the vertices of the digraph can be colored with k colors and each color class induces an acyclic digraph. It is easy to see that both notions coincide in the symmetric case, where an arc exists if and only if its antiparallel also exists. Moreover Neumann-Lara conjectured that every orientation of a simple planar graph can be acyclically colored with two colors. Regarding the dichromatic number this is not the only conjecture remaining widely open. Applications can be found in scheduling and deadlock resolution, where the size of acyclic subdigraphs plays an important role. With our work we contribute to a better understanding of the dichromatic number. Hochstättler developed a flow theory transferring Tutte's theory of NZ-flows from classical graph colorings to acyclic colorings of digraphs. Together with Altenbokum we pursued this analogy by introducing algebraic Neumann-Lara-flows (NL-flows) as well as a polynomial counting them. In this talk we will present a representation of the dual of this NL-flow polynomial, which is closely related to the chromatic polynomial of a digraph, counting acyclic colorings.

2 - Directed Acyclic Graphs and Digraph Colorings
Ararat Harutyunyan

A Directed Acyclic Graph (or a DAG) is a directed graph which does not contain a directed cycle. DAGs appear everywhere in computer science and their applications in telecommunications, sorting, scheduling, data compression, and data processing are ubiquitous. This importance partially stems from the fact that many optimization problems that are hard on general digraphs are easy on DAGs. Curiously enough, compared to their practical importance, fundamental knowledge and understanding of DAGs is not as broad or deep as one would like. For example, how large of a DAG can one find as a subdigraph in a general digraph?

Similarly, one can consider DAG-partitionings of a general digraph. In k-Digraph Coloring, we are given a digraph and are asked to partition its vertices into atmost k sets, so that each set induces a DAG. This well-known problem is NP-hard, as it generalizes(undirected) graph k-Coloring, but becomes trivial if the input digraph is acyclic. This poses the natural parameterized complexity question: what happens when the input is "almost" acyclic. In this talk, we will present some algorithmic results answering this question using parameters that measure the input's distance to acyclicity. In particular, our parametrisations are in terms of feedback vertex/arc sets and treewidth. For example, one of the tight results we obtain is that the problem remains NP-hard even if the digraph has feedback vertex set of size only k. This is joint work with Michail Lampis and Nikolaos Melissinos.

3 - From Counting Matchings to Digraph Coloring
Raphael Steiner

A coloring of a digraph as defined by Erdős and Neumann-Lara is a vertex-coloring avoiding monochromatic dicycles. The minimal number of colors required for such a coloring of a digraph is defined to be its dichromatic number. This quantity has been widely studied in the last decades and can be considered a natural directed analogue of the chromatic number of a graph. A digraph is called even if for every 0-1-weighting of the edges it contains a directed cycle of even total weight. I will sketch a proof that every non-even digraph has dichromatic number at most 2 and that an optimal coloring can be found in polynomial time. We then exhibit a surprising reformulation of this result in terms of partitions of perfect matchings in Pfaffian graphs. The latter play an important role in the task of efficiently counting the number of perfect matchings of a given graph, and are strongly related to nonsingularity problems in linear algebra.

4 - Oriented vertex and arc coloring of edge series-parallel digraphs
Marvin Lindemann, Frank Gurski, Dominique Komander

In this talk we study the oriented vertex and arc coloring problem on edge series-parallel digraphs which are related to the well known series parallel graphs. Series parallel graphs play an important role in theoretical computer science. The oriented class of series parallel digraphs is recursively defined from pairs of vertices connected by a single arc and applying the parallel and series composition, which leads to specific orientations of undirected series-parallel graphs. We reprove the known bound of seven for the oriented chromatic number and the oriented chromatic index of series parallel digraphs and we show that these bounds are tight even for edge series parallel digraphs. Furthermore, we give linear time solutions for computing the oriented chromatic number and the oriented chromatic index of minimal series parallel digraphs and edge series-parallel digraphs.

■ TA-05

Thursday, 9:00-10:20 - Mönch

Software for OR - Solvers III

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Michael Bussieck*

1 - Black-box expressions in CP Optimizer
Paul Shaw

We present the black-box expression support in CP Optimizer, the constraint programming engine of CPLEX Optimization Studio. This black-box support allows the user to invoke arbitrary code to calculate the value of any expression of the model from its sub-expressions. One could, for example, evoke a simulation, call opaque library code, use a machine learning prediction model, and so on. Black-box expressions can be used as terms in the objective, be constrained, or even form part of higher-level black-box expressions.

In this talk, we will try to give the listener an appreciation of the new kinds of optimization model that it is possible to write and solve using black-box expressions. We will first give a brief introduction to black-box expressions in CP Optimizer, and then go on to demonstrate their usefulness, generality and ease of use through intuitive worked examples.

2 - Distributed Solving of Mixed-Integer Programs with COIN-OR CBC and Thrift
Jochen Rethmann, Jakob Görner, Ramon Janssen

We present an easy-to-use and free-of-charge distributed branch and bound solver for mixed-integer programming (MIP) problems. Our aim is to provide an alternative to commercial solvers like CPLEX and Gurobi so that even small or medium-sized companies come to the benefit of an optimization suite. Licences of commercial solvers are often not affordable for small companies. The solver utilizes the Computational Infrastructure for Operations Research (COIN-OR) branch-and-cut solver (CBC) for solving subproblems. Interprocess communication is achieved by using the remote procedure call (RPC) library Thrift. Using ordinary office hardware, we evaluate our solution on instances from the MIPLIB and multidimensional knapsack instances both in deterministic and non-deterministic mode.

3 - On affine conic and disjunctive constraints in the upcoming Mosek version 10
Erling Andersen

Mosek is a widely used optimization software pacakage for large-scale, possibly mixed-integer linear and conic optimization problems. A novelty in the upcoming Mosek version 10 is the introduction of affine conic and disjunctive constraints. These two features make it easier to express continous conic and discrete optimization problems. In this presention we will discuss why and how these features have been introduced into Mosek.

4 - Global Nonlinear Pricing in the Simplex Method

Biressaw Wolde, Torbjörn Larsson

We present an approach for general linear programming based on global nonlinear pricing and feasible directions. The approach is embedded in the framework of the simplex method, through the use of external columns, which are combinations of original columns. The global nonlinear pricing function is composed by the ordinary linear pricing function of the simplex method, which captures the behaviour of the objective function over the set of feasible directions, and a nonlinear penalty function that captures global information about the topology of the feasible polyhedron. Given a basic feasible solution, the nonlinear pricing problem yields a non-edge improving feasible direction, which is converted into an external column that enters the basis.

Our approach allows many computational strategies. First, an external column may be generated seldomly or often. Second, the nonlinear pricing problem can be solved accurately or approximately. Third, it is possible to consider low-dimensional restrictions of the nonlinear pricing problem, which can give good enough improving feasible directions. Preliminary computational results indicate that the use of global nonlinear pricing may have a significant advantage over the ordinary pricing method of the simplex method.

■ TA-06

Thursday, 9:00-10:20 - Jungfrau

Stochastic Optimization

Stream: Discrete and Combinatorial Optimization, sponsored by FICO

Invited session

Chair: *Steffen Rebennack*

Chair: *Christian Füllner*

1 - Discretization of Markov Processes for Stochastic-dynamic Optimization

Nils Löhndorf

In multistage stochastic programming or approximate dynamic programming, descretization of high-dimensional stochastic processes is often inevitable. We propose a second-order learning algorithm to discretize Markov processes to scenario lattices which can be used to solve multistage stochastic programs using stochastic dual dynamic programming. Unlike first-order methods, our method does not require manual calibration of stepsize rules but adjusts the stepsize automatically by learning an approximation of the Hessian. We prove convergence of the learning algorithm and demonstrate that it is capable of producing lattices that yield near-optimal solutions when compared with a known bound from the extant literature. Numerical results indicate that the second-order method achieves lower Wasserstein distances and leads to better policies than simple first-order methods.

2 - Non-convex Benders decomposition

Christian Füllner, Steffen Rebennack

We propose a new decomposition method to solve multistage non-convex mixed-integer (stochastic) nonlinear programming problems (MINLPs). We call this algorithm non-convex nested Benders decomposition (NC-NBD).

NC-NBD is based on solving dynamically improved mixed-integer linear outer approximations of the MINLP, obtained by piecewise linear relaxations of nonlinear functions. Those MILPs are solved to global optimality using an enhancement of nested Benders decomposition, in which regularization, dynamically refined binary approximations of the state variables and Lagrangian cut techniques are combined to generate Lipschitz continuous non-convex approximations of the value functions. Those approximations are then used to decide whether the approximating MILP has to be dynamically refined and in order to compute feasible solutions for the original MINLP. We prove that NC-NBD converges to an approximately optimal solution in a finite number of steps.

Computational results indicate that the decomposition approach is best suited for (stochastic) problems with many stages and a moderate number of state variables.

3 - Robust optimization models for MRP - a comparison to stochastic programming approaches and a decomposition based solution method

Manuel Schlenkrich, Sophie Parragh

This paper investigates robust optimization models for Material Requirements Planning (MRP). The addressed optimization problem is the multi-item multi-echelon capacitated lot-sizing problem with constant lead times under uncertain demand. The presence of stochasticity in the demand for end items in a production system can have significant influence on optimal production quantities and the resulting inventory- and backlog levels. Neglecting this uncertainty within the optimization model by solving a deterministic version of the problem with uncertain parameters replaced by their averages, results in suboptimal production plans. While tackling this issue by using scenario-based stochastic optimization assumes knowledge of probability distributions, robust optimization serves as a worst-case approach and comes with great potential in reducing computational complexity. Especially for large scale problems with complex manufacturing structures efficient modelling and solution methods are desirable. This paper compares solutions obtained by two-stage stochastic programming techniques to robust solutions concerning two characteristics. On the one hand computational complexities of both approaches are compared, while on the other hand the structures and qualities of the obtained solutions are analysed. A simulation framework is used to evaluate the performance of the different resulting production plans in an uncertain environment. Since solving stochastic programs with a large number of scenarios is computationally challenging, this paper also introduces a solution method based on Benders Decomposition tailored to the observed production planning problem, in order to obtain results for the comparison of both frameworks in reasonable time.

■ TA-07

Thursday, 9:00-10:20 - Niesen

Learning-Augmented Algorithm Design

Stream: Discrete and Combinatorial Optimization, sponsored by FICO

Invited session

Chair: *Nicole Megow*

1 - Learning-Augmented Algorithms

Antonios Antoniadis

The design of learning-augmented algorithms is a novel area that combines two well-established approaches for tackling optimization problems: On one hand, classical algorithm analysis provides worst-case performance guarantees, but by its worst-case nature it can be quite pessimistic in many input instances that are far from the worst-case. On the other hand, machine-learning approaches have proven to be extremely effective in common input instances that are accounted for in the training data, but may exhibit arbitrary bad performance on inputs that are not sufficiently represented in the training data.

In learning-augmented algorithms, a machine-learning approach provides predictions (of unknown quality) regarding the current input instance or the structure of the desired solution. The goal of the algorithm designer is to utilize these predictions in order to (i) obtain performance comperable to that of the machine-learning approach in case the predictions were adequate, while at the same time (ii) provide a worst-case performance guarantee not too far off from that of the best known classical algorithm for the problem. The later is important for inputs of highly imprecise predictions. This approach has been employed successfully in designing algorithms that are of theoretical as well practical interest.

In this talk we give a brief overview of learning-augmented algorithms before discussing some of our recent results in the area.

2 - Learning Augmented Energy Minimization via Speed Scaling

Etienne Bamas

As power management has become a primary concern in modern data centers, computing resources are being scaled dynamically to minimize energy consumption. Motivated by this major issue, various scheduling problems about energy minimization appeared in the literature.

In this talk, I will focus on a variant of the classic online speed scaling problem introduced by Yao et al. (FOCS 1995), in which machine learning predictions about the future can be integrated naturally. More precisely, I will show how to design an algorithm which incorporates predictions in a black-box manner and outperforms any online algorithm if the accuracy is high, yet maintains provable guarantees if the prediction is very inaccurate. I will discuss both theoretical and practical results.

This is based on a joint work with Andreas Maggiori (EPFL), Lars Rohwedder (EPFL), and Ola Svensson (EPFL).

3 - Robustifying Untrusted Methods for Online Graph Exploration

Jens Schlöter, Franziska Eberle, Alexander Lindermayr, Nicole Megow, Lukas Nölke

The online graph exploration problem is motivated by robot navigation and exploration of unknown terrain. Starting at a given vertex, the goal is to visit all vertices of an, initially unknown, undirected graph by traversing edges, while minimizing the total traversal costs. When a vertex is visited for the first time, all incident edges and their traversal costs are revealed. The best-known algorithm achieves a competitive ratio logarithmic in the number of vertices [Rosenkrantz et al., 1977], and there are several algorithms with an improved ratio for special cases, e.g., planar graphs [Kalyanasundaram and Pruhs, 1994, Megow et al., 2012]. However, in general, it is unknown whether a given graph meets the criteria of such a special case before it is explored, and applying special-case algorithms to arbitrary graphs may lead to a much worse or possibly unbounded competitive ratio. We introduce a robustification scheme that, given an arbitrary (e.g. special-case) algorithm for the online graph exploration problem, robustifies its worst-case guarantee for arbitrary graphs. The robustification scheme achieves a competitive ratio that, asymptotically, matches the minimum of the competitive ratios of the given algorithm and the best-known algorithm for general graphs. Thus, it can be used to exploit algorithms for special cases, without losing if the special case does not occur. Further, we show how to implement our scheme in a learning-augmented setting and benefit from access to (error-prone) predictions. Given an algorithm that relies on a high quality of the predictions, the scheme gives a near-optimal solution while being robust to arbitrarily wrong predictions. Joint work with F. Eberle, A. Lindermayr, N. Megow, L. Nölke (University of Bremen).

4 - The balanced maximally diverse grouping problem with attribute values and varying group sizes

Arne Schulz

The balanced maximally diverse grouping problem with attribute values and varying group sizes (BMDGPAVVG) searches for the best balanced solution amongst all optimal solutions of the corresponding instance of the maximally diverse grouping problem with attribute values and varying group sizes (MDGPAVVG). We describe the set of optimal solutions of MDGPAVVG which allows us to use a short integer program presented in the literature to solve the BMDGPAVVG.

■ TA-08

Thursday, 9:00-10:20 - Stockhorn

Gas networks and markets

Stream: Energy and Environment
Invited session
Chair: *Dominik Möst*
Chair: *Russell McKenna*
Chair: *Steffen Rebennack*

1 - Modeling and forecasting gas network flows with multivariate time series and mathematical programming approach

Nazgul Zakiyeva, Milena Petkovic

With annual consumption of approx. 95 billion cubic meters and similar amounts of gas transhipped through Germany to other EU states, Germany's gas transport system plays a vital role in European energy supply. The complex, more than 40,000 km long high-pressure transmission network is controlled by several transmission system operators (TSO) whose main task is to provide security of supply in a cost-efficient way. Given the slow speed of gas flows through the gas transmission network pipelines, it has been an essential task for the gas network operators to enhance the forecast tools to build an accurate and effective gas flow prediction model for the whole network. By incorporating the recent progress in mathematical programming and time series modeling, we aim to model natural gas network and predict gas in- and out-flows at multiple supply and demand nodes in the network. Our model is able to describe the dynamics in the network by detecting the key nodes as well as the significant exogenous variables (local temperature, nomination history, and others), which may help to build an optimal management strategy for transmission system operators.

2 - Blending hydrogen into natural gas - An assessment of the capacity of the German gas grid

Jaap Pedersen, Kai Hoppmann-Baum, Janina Zittel, Thorsten Koch

In the transition to a pure hydrogen infrastructure, utilizing the existing natural gas infrastructure is a necessity. In this study, the maximal technically feasible injection of hydrogen into the existing German natural gas transmission infrastructure is analysed with respects to regulatory limits for gas quality. Therefore, we propose a transient tracking model based on the general pooling problem including linepack. The analysis is performed on hourly gas flow data of one of Europe's largest transmission network operators, which operates a network of about 12,000 km length.

3 - Statistical analysis and modeling for detecting regime changes in gas nomination time series

Milena Petkovic, Nazgul Zakiyeva, Janina Zittel

As a result of the legislation for gas markets introduced by the European Union in 2005, separate independent companies have to conduct the transport and trading of natural gas. The current gas market of Germany, which has a market value of more than 54 billion USD, consists of Transmission System Operators (TSO), network users, and traders. Traders can nominate a certain amount of gas anytime and anywhere in the network. Such unrestricted access for the traders, on the other hand, increase the uncertainty in the gas supply management. Some customers' behaviors may cause abrupt structural changes in gas flow time series. In particular, it is a challenging task for the TSO operators to predict gas nominations 6 to 12 hours ahead. In our study, we aim to investigate the time series of nominations and build a time series model that can detect the regime change and predict up to 12 hours ahead of gas nominations.

4 - Research trends in combinatorial optimisation

Russell McKenna, Jann Weinand, Kenneth Sörensen, Pablo San Segundo, Max Kleinebrahm

Real-world problems are becoming highly complex and, therefore, have to be solved with combinatorial optimisation (CO) techniques. Motivated by the strong increase of publications on CO, 8,393 articles from this research field are subjected to a bibliometric analysis. The corpus of literature is examined using mathematical methods and a novel algorithm for keyword analysis. In addition to the most relevant countries, organisations and authors as well as their collaborations, the most relevant CO problems, solution methods and application areas are presented. Publications on CO focus mainly on the development or enhancement of metaheuristics like genetic algorithms. The increasingly problem-oriented studies deal particularly with real-world applications within the energy sector, production sector or data management, which are of increasing relevance due to various global developments. The demonstration of global research trends in CO can support researchers in identifying the relevant issues regarding this expanding and transforming research area.

■ TA-09

Thursday, 9:00-10:20 - Gantrisch

Data Analytics, Forecasting & Simulation

Stream: Systems Modeling and Simulation
Invited session
Chair: *Andrea Emilio Rizzoli*
Chair: *Maximilian Moll*

1 - Study of degrading systems subject to stochastic arrival times

Lucía Bautista Bárcena, Inmaculada Torres Castro

A system subject to multiple degradation processes is analyzed. We assume that the degradation processes start at random times following a Cox process. Cox processes are a generalization of the Poisson process in which the intensity of arrivals is stochastic in itself. We assume that the Cox process driven by a shot-noise process. This means that the system is subject to shots according to a Poisson process. In addition, the shot-induced stress is additive and decays with time according to a classical exponential function.

Once the degradation process starts, the degradation of the process evolves following a gamma process. Gamma process is considered one of the most appropriated processes for modelling the damage produced by cumulative deterioration of systems. We show that the combined process of arrival and growth of the degradation processes follow a Cox process with stochastic intensity.

We assume that the system fails when the degradation level of a degradation process exceeds a failure threshold. Under this framework, the survival function of this system is obtained. It is also shown that the survival function of this system is increasing failure rate.

2 - The Issue of Multi-Tasking: Analyzing Difficulties in Predicting Multi-Issue Decision Outcomes

Stefan Wolfgang Pickl, Jacob Ehrlich, Maximilian Moll, Leonhard Kunczik

As technology, data, and theoretic academic foundations mature, prediction tool capabilities become more reliable and able to handle increasingly complex situations. Of particular interest is the modeling of interactions between stakeholders involved in political decision-making for the purpose of prediction. Scenarios in this manner provide limited observability due to the sensitive nature of the decision-making process. The transition from theoretic and laboratory success to models with practical application ushers subsequent challenges of uncertainty towards the rounds of stakeholder interactions before a final decision is made. Success nonetheless has been found using the expected utility models provided by Bruce Bueno de Mesquita. This paper introduces an implemented model built from the more complex conceptual framework laid out in his work. The implemented model is applied to the DEU dataset concerning European decision-making. While the model accurately captures the result of some issues, predictive success is limited on the dataset as a whole. The objective becomes properly understanding these shortcomings.

3 - Simulation study to identify the influence of systematic and unsystematic forecast behavior on safety stock for an MRP system with rolling horizon forecast updates

Wolfgang Seiringer, Klaus Altendorfer, Thomas Felberbauer, Fabian Brockmann

This paper investigates the customer forecast behavior of changing order amounts when due date is getting closer and its impact on inventory and backorder costs. Customer behavior can be systematic in form of booking too much or too less and unsystematic with no distinct observable behavior, i.e. a random noise. These demand forecast changes introduce uncertainty into the production system and have negative impact on performance and costs. For a multi-item capacitated production system applying a Material Requirements Planning (MRP) planning scheme, the influence of safety stock for finished goods on inventory and backorder costs is evaluated. Simulation is applied to model the stochastic process of demand forecast updates, the MRP planning scheme, and the stochastic production system behavior. The investigated production system is two-staged including a two level bill-of-materials with eight finished goods and four semi-finished materials. The provided demand forecasts, which are updated on a rolling horizon basis, are used as gross requirements for the MRP run. The demand model follows the Martingale Model of Forecast Evolution Model (MMFE) extended by forecast biases revealed certain periods before delivery. Applying a planned lead time for MRP, this implies that production orders are generated based on uncertain gross requirements. Several scenarios on the demand model parameterization are tested and a finite solution space for the MRP planning parameter safety stock is enumerated. This numerical study presents first results on the influence of uncertainty level and biased forecast changes on MRP planning parameter safety stock and further research is planned to also include other planning parameters.

4 - What the heat is going on? Long-term forecast of heating demand in Munich with data analytics and simulation

Maik Günther, Andreas Müller, Benedikt Baus

Decarbonization of the heating sector is very important to achieve climate targets. The district heating system of Munich's utility the Stadtwerke München GmbH (SWM) is among the largest in Europe. One of SWM's ambitious decarbonization goals is the long-term decarbonization of the district heating supply. This should be realized primarily with geothermal energy. In order to achieve this goal at optimal cost, it is important to have a good knowledge of the spatially resolved heat demand in long-term. For this reason, SWM developed a model, the 'Modell München'. It contains detailed information about the buildings: addresses, floors, residential units, living space, construction period, used heating system, heating demand as well as shapes. This model is based on various data sources. Data gaps were closed using machine learning. For future projections of the long-term heating demand and the used heating technology until 2050, SWM teamed up e-think energy research, a spin-off of the EEG of the TU Wien. The Modell München was integrated into the Invert/EE-Lab model of e-think. Invert/EE-Lab is a bottom-up simulation model. It calculates the probabilities of retrofit measures for each building in Munich under different policy measures, energy prices, technology costs and the availability of energy carriers. By aggregating the probabilities, the model provides a spatial distribution of expected final energy consumption for each building across the city. The results of the model help SWM to better understand the dynamics of future demand and to set focused measures to reach the decarbonization target. In addition, the results are important for investment decisions in plants for geothermal energy and for investments in the district heating grid.

■ TA-10

Thursday, 9:00-10:20 - Schreckhorn

Logistics in the pandemic crisis

Stream: Logistics and Freight Transportation
Invited session
Chair: *Karl Doerner*

1 - A Large Neighbourhood Search Metaheuristic for the Contagious Disease Testing Problem

David Wolfinger, Margaretha Gansterer, Karl Doerner, Nikolas Popper

In late 2019 a new coronavirus disease (COVID-19) emerged, causing a global pandemic within only a few weeks. A crucial factor in the public health response to pandemics is achieving a short turnaround time between a potential case becoming known, specimen collection and availability of a test result. In this article we address a logistics problem that arises in the context of testing potential cases. We assume that specimens can be collected in two ways: either by means of a mobile test-team or by means of a stationary test-team in a so called (drive-in) test-centre. After the specimens have been collected they must be delivered to a laboratory in order to be analysed. The problem we address aims at deciding how many test-centres to open and where, how many mobile test-teams to use, which suspected cases to assign to a test-centre and which to visit with a mobile test-team, which specimen to assign to which laboratory, and planning the routes of the mobile test-teams. The objective is to minimise the total cost of opening test-centres and routing mobile test-teams. We introduce this new problem, which we call the contagious disease testing problem (CDTP), and present a mixed-integer linear-programming formulation for it. We propose a large neighbourhood search metaheuristic for solving the CDTP and present an extensive computational study to illustrate its performance. Furthermore, we give managerial insights regarding COVID-19 test logistics, derived from problem instances based on real world data.

2 - The Contagious Disease Testing Problem - A scenario analysis
Jana Lepping, David Wolfinger, Karl Doerner, Margaretha Gansterer, Martin Bicher, Nikolas Popper

Fighting the COVID-19 pandemic involves an extensive testing strategy. As part of it, potentially infected persons showing symptoms and their contact persons need to undergo a Polymerase-Chain-Reaction (PCR) test in a timely manner. The PCR tests are either carried out in a test centre, to which potentially infected persons travel themselves, or they get visited by a mobile test team at home. After having conducted a test, the swab needs to be evaluated in a laboratory. This scenario analysis aims at providing managerial insights on how different numbers of available test centres, while keeping the number of available mobile test teams constant over all scenarios, influence the total costs of operating test centres and routing mobile test teams. The analysis is based on the Contagious Disease Testing Problem (CDTP), solved with a large neighbourhood search metaheuristic. We conducted an extensive computational study focusing on three scenarios with different numbers of available test centres. For each scenario, we investigated three different phases of the pandemic in order to take into consideration the fluctuating number of PCR tests which have to be conducted as per official order on a given day. Moreover, we strived to achieve a comparison of the impact varying numbers of available test centres have on an urban and a rural setting. Therefore, we applied the scenarios to the Austrian provinces of Vienna, representing an urban area, and Upper Austria, representing a rural area.

3 - Vehicle routing for a population-wide COVID-19 testing program
Emilio Jose Alarcon Ortega, Margaretha Gansterer, Karl Doerner

During the recent pandemic scenario, a wide range of logistics problems arise. One of the recent strategies applied by national governments is related to gargling tests. Due to pooling techniques, these can be used to perform regular mass testings. However, in order to provide testing results in short time, an efficient logistics network has to be developed. We investigate such a network for a population-wide testing program initiated by the City of Vienna. In this program, all citizens are encouraged to perform gargling tests at home. Used testkits can be returned in retail stores and gas stations, from where they are picked up and delivered to a laboratory. We present a mathematical formulation that resembles the real-world problem related to the pick up of CoVid-19 gargle tests from these return stations, which are spread all over the City of Vienna. The problem is formulated as a multi-period vehicle routing problem where the customers require consistency in the arrival times at the locations and consistency of the drivers. Furthermore, it is possible to reduce the service times at the locations by increasing the number of drivers on each vehicle from one to two drivers. Furthermore, we study the impact of considering a transshipment location, as the laboratory is located outside of the city area. By introducing this transshipment node, we can reduce total costs. However, the transshipment point can store a maximum number of testkits that, afterwards, will be sent to the laboratory in a big capacity vehicle. To solve this problem, we propose a heuristic method that combines a cheapest insertion constructive heuristic with an adaptive large neighborhood search. An extensive computational study reveals interesting insights on this challenging real-world problem.

4 - Layout and location planning for automatic locker box systems under stochastic demand
Michael Kahr, Karl Doerner, Margaretha Gansterer

The pandemic caused by the corona virus SARS-Cov-2 imposed many challenges to humanity. Besides health-care issues, a large increase in demand for home deliveries triggered by lockdowns and stay-at-home orders was observed. A potential gear to cushion such increased demand regards the mode of transport at the last mile. Appropriate transportation concepts during pandemics include performing last-mile delivery via (outdoor) automatic locker box systems where customers can collect their orderings 24/7 while ensuring social distancing. The location decision of such locker box systems is known to be crucial for their success. A challenging aspect regards uncertain customer demand for different commodities and therefore also deciding location-specific layouts of installed locker box systems. The latter challenges are addressed and the new stochastic multi-compartment locker location problem is proposed. The objective is to maximize the expected utility of the covered customer-demand given a budget an operator is willing to invest. An integer linear programming formulation is proposed together with an exact reformulation based on Benders decomposition. It is shown that each Benders cut can be separated in linear time. The proposed algorithms allow to solve large-scale instances to proven optimality in reasonable time. Besides computational results on artificial instances, a case study for Austria's capital Vienna is presented.

■ TA-11

Thursday, 9:00-10:20 - Wildstrubel

Financial Markets

Stream: Finance
Invited session
Chair: *Julian Schneider*

1 - Fraud Detection by using Isolation Forests
Johannes Kriebel, Jörn Debener, Volker Heinke

Fraud is a significant issue to insurers. The associated costs have to be reflected in insurance premia and are, therefore, harmful to honest policyholders. The question arises as to how insurance fraud can best be detected. Prior literature has started to study the use of machine learning methods to detect insurance fraud. However, most studies rely on methods based on supervised learning such as logistic regression and neural networks. In the context of insurance fraud, these methods are prone to two important shortfalls, overfitting due to few labelled cases and overfitting of already known fraud patterns. To address this problem, we use isolation forests, a new method of unsupervised learning. Isolation forests are an ensemble of trees that detect anomalies. We analyze a large proprietary data set of over 30,000 German automobile insurance claims. We build four different isolation forests to capture the complex character of insurance fraud: We model the anomaly of the claimed amount, of the description of the accident, of the way of reporting of the accident, and of the economic motivation for the policyholder. Thus, we obtain four anomaly scores for every claim in the data. In a validation analysis, we assess whether the anomaly scores can identify fraud. Our results show that the anomaly scores significantly predict fraud. This is also the case taking the risk score from an in-house automated rule-based fraud detection system into account. Interestingly, the anomaly scores are particularly helpful in detecting those fraudulent claims that were detected manually (i.e., not by the automated system). Thereby, we show that isolation forests can assist methods based on already identified fraud cases in the process of detecting unknown patterns of insurance fraud.

2 - Does firm's silence drive media's attention away?
Sasan Mansouri

In this study, using a comprehensive dataset on business media coverage and textual analysis of the discussions in firms' quarterly earnings conference calls, we show that when management fails to satisfy the demand for information, ceteris paribus, their firms receive less media coverage. Poor information environment hurts the information-creation capacity of the media, while such an environment does not show a similar association with the media's information-dissemination role. Furthermore, this association is more prominent for professional business media, compared to their non-professional counterparts such as blogs and alternative articles. Our results add nuance to the literature on media coverage bias by showing that supply-side factors, i.e. the factors affecting the suppliers of the coverage, mainly drive the coverage of firms, not the demand.

3 - On the externalitites of tech firms
Kai Rohde, Peter Grundke, Valeriya Dinger

The political debate about the potential risks stemming from the size and market influence of digitally-oriented tech companies has intensified in recent years resulting in calls to split large tech companies in order to limit their market power and the degree of externalities these firms can exert over other areas of the economy. However, there exists so far, no quantitative estimate of these externalities. In this paper, we close this gap by applying market-based systemic risk measures originally designed for financial firms to measure the externalities of tech firms included in the S&P 500 index. Our results show that tech firms in general are characterized by a high and rising level of externalities. For this, we run random-effects panel regressions with several control variables and time-fixed effects on a yearly basis for the time period 2012 to 2019. We also identify subsectors within the tech industry with a particularly high level of externality. We show that while platform firms and the well-known GAFAs do not exert higher levels of externalities than other tech firms, semiconductor firms are characterized by particularly high levels of externalities. Further, we explore whether balance sheet characteristics are significantly correlated with the measured degrees of externalities for tech firms and find that this is not the case. Finally, we present evidence that the measures of externalities of tech firms are particularly high when the computation of the employed measures is based on filtered equity returns. Doing this, we filter out the effect of an exposure to systematic risk factors. This indicates that tech firms exert strong externalities through direct interactions (e.g., direct business relationships) with other firms.

4 - Competition for Visibility: When do (FX) Signal Providers employ Lotteries?
Julian Schneider, Andreas Oehler

We argue that certain currency pairs - similar to stocks - are perceived and employed as gambling opportunities. Motivated by Bali, Cakici, and Whitelaw (2011), we define currency pairs with extreme positive daily returns as lotteries. By analyzing data from a popular foreign exchange focused social trading platform, we provide empirical evidence of a quadratic (U-shaped) relationship between previous relative trader performance and the traded lottery share: Traders with bad performance and traders with good performance, in comparison to their peers, are more prone to gamble, i.e. trade a higher monthly share of lotteries. We link our results to well-documented behavioral phenomena like the house money effect, the break-even effect (Thaler and Johnson (1990)), and overconfidence (Barber and Odean (2001), Broihanne, Merli, and Roger (2014), De Long et al. (1991), Odean (1999)). Finally, we argue that remuneration design features common to social trading induce traders to compete for visibility. Thus, after (repeatedly) performing poorly, traders might be willing to take gambles for a small chance to get a declining account back on track.

■ TA-12
Thursday, 9:00-10:20 - Faulhorn

Dial-a-Ride Problems I

Stream: Mobility and Traffic
Invited session
Chair: *Lennart Johnsen*

1 - A static dial-a-ride problem with ride and waiting time minimization
Christian Pfeiffer, Arne Schulz

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 neighborhood search (ALNS) as well as a dynamic programming algorithm (DP). 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.

2 - Multimodal commuter ride sharing with flexible interchanges and return trip planning
Georg Brandstätter, Matthias Prandtstetter

In suburban areas, commuters frequently use cars to get to work. Even those who commute by public transport often need a car to reach the nearest train station. This inefficient use of vehicles, which can lead to traffic congestion and overcrowded parking facilities near popular interchanges, could be mitigated by improving vehicle occupancy rates.

In a ride sharing system, drivers who are willing to take on passengers can announce their planned trips in advance. Similarly, prospective passengers can enter their desired itinerary and be matched to drivers with compatible schedules and routes. The system can then find suitable meeting and interchange locations and optimizes the joint routes.

We describe an algorithm for matching passengers to drivers and planning their joint routes. Given a set of itineraries for drivers and passengers, each with potentially multiple paths (via different interchanges) to their final destination, we match passengers to drivers according to schedule compatibility and proximity along these paths, find concrete travel routes for each user and determine pick-up and drop-off locations accordingly. To ensure high user satisfaction, the morning and evening commutes of each user are planned together.

We evaluate this algorithm on a set of benchmark instances derived from data provided by a ride sharing company operating in the metropolitan area of Vienna and compare it to their currently implemented dynamic first-come-first-served approach.

3 - The Balanced Charging Problem
Miriam Ganz, Erik Mühmer, Marco Lübbecke

The Balanced Charging Problem (BCP) deals with the allocation of electric vehicles (EV) to charging stations, taking into account the load of the underlying energy network in addition to the charging demands. The goal is to balance the load on the energy network as much as possible so that overloads are avoided. We present two exact approaches based on mixed integer linear programming. A discrete-time approach allows a more accurate estimation of the load caused by EV charging, given the charging profiles of the EVs under consideration. Moreover, we consider a scheduling approach which does not require knowledge of such. For this purpose, we assume that charging takes place with full available load over the entire charging period. Finally, we compare the presented approaches regarding their performance and discuss the results of our computational studies.

4 - The dial-a-ride problem with stochastic interrelated trips
Lennart Johnsen, Jan Fabian Ehmke, Frank Meisel

In this paper, we introduce a stochastic variant of the dial-a-ride problem with interrelated trips. Interrelated trips are transportation requests, where users ask for simultaneous arrival at meeting locations, where round trips involve a stay time at some destination locations, or the like. In such complex transportation schedules, user lateness is especially challenging and delays can likely propagate through the tours of other vehicles. In this paper, we look at smart ways of how to make these systems more reliable and attractive. In our approach, we carefully consider how to compute the start-service times and arrival time distributions of the vehicles at each customer location. With these distributions, we create a feasibility check to construct more reliable schedules. Our computational experiments investigate the effectiveness of our approach as well as the interaction between customer service and the system's cost and availability.

■ TA-13
Thursday, 9:00-10:20 - Blüemlisalp

Theory of Revenue Management

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

1 - Risk-averse network revenue management
Martin Glanzer, Christiane Barz

In this talk, we discuss the network capacity control problem in a risk-averse setting. In particular, we use an exponential utility function to control the risk-aversion. The problem suffers from a massive curse of dimensionality and thus typically cannot be solved exactly by standard dynamic programming techniques. In the risk-neutral setting, the problem has successfully been tackled in the literature by an approximate dynamic programming (ADP) approach with an affine approximation of the value function. This leads to a particularly pleasant problem structure, both theoretically and from a computational perspective. We discuss that in our risk-averse setting, an analogously simple approach leads to useless decision policies. We therefore propose an ADP approach where the value function is approximated by a monomial. For this approach, we show some structural results and argue that the resulting policy has appealing properties that cannot be obtained by simpler forms of approximations. From a computational perspective, the resulting problem is highly nonlinear. However, it can be formulated in the form of a signomial/reversed geometric program. In recent years, substantial progress has been made in terms of available software for signomial programming. Thus, our proposed approach is promising also from a computational perspective. Some numerical examples complete the talk.

2 - Towards Transfer Learning for Revenue and Pricing Management
Alexander Kastius

Reinforcement Learning has proven itself as a powerful tool to optimize pricing processes. With the support of deep non-linear function approximation tools, it can handle complex and continuous state and action spaces. This ability can leverage the utility of pricing algorithms in markets with a vast number of participants or in use-cases where additional product features should be taken into account in the pricing system. One problem with those tools is their apparent demand for training data, which might not be available for a single market. We propose to use techniques instead, which leverage the knowledge of different problems. Several similar algorithms have been proposed in the past years to allow reinforcement learning algorithms to operate efficiently on various processes simultaneously. One example is DISTRAL, which continuously merges information from different decision processes towards a distilled policy and uses the joint policy to update the market-specific source policies. We will discuss the influence of such regularization mechanisms. Multi-market pricing problems are used to illustrate their impact.

3 - Stochastic Dynamic Pricing under Duopoly Competition with Mutual Strategy Adjustments
Rainer Schlosser, Alexander Kastius

In practical applications, firms use data-driven dynamic pricing strategies to increase their rewards in the presence of competition. Merchants are forced to steadily adjust their strategies in response to changing market environments caused by competitors that update their pricing strategies over time. In this paper, we study mutual updates of dynamic pricing strategies in an infinite horizon duopoly model with stochastic demand. We use dynamic programming techniques to compute strategies that take anticipated price reactions of the competitor into account. We consider cases in which (i) strategies are mutually observable and (ii) have to be identified from single price observations over time. For both scenarios, we analyze and compare the long-term interaction of competing self-adaptive strategies.

4 - Contracting strategies for price competing firms under uncertainty
You Wu, Benny Mantin, Anne Lange

We study interactions between multiple capacity-constrained asset providers and multiple logistics service providers (LSPs) who trade transport capacities on a spot market. In the spot market, the asset providers compete over prices. Prior to entering the spot market, the asset providers and the LSPs face demand uncertainty. To circumvent demand uncertainty, an asset provider and an LSP can negotiate a contract to secure sales and capacity, respectively. By signing such a contract, they effectively reduce both supply and demand in the spot market and, hence, it is not clear how spot prices are affected. 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 asset provider and an LSP. In the second stage, after demand is realized, the spot market brings together the LSPs—who aggregate demand not satisfied through their negotiated capacity—and the asset providers—who bring their remaining uncontracted capacity. Solving the game backwards, we characterize the sub-game perfect Nash equilibrium. We find the optimal pricing strategies in the spot market may involve mixed pricing strategies for certain demand ranges, specifically, if demand is not too high or too low. Analyzing the bargaining stage, we assume uniformly distributed demand and numerically we characterize the contracts that generate more benefits to both agents: when potential demand is low and when the LSPs charge a low margin for their services.

■ TA-14

Thursday, 9:00-10:20 - Wetterhorn

Data Mining Techniques

Stream: Analytics
Invited session
Chair: *Jochen Gönsch*
Chair: *Davina Hartmann*

1 - The Max-Cut Decision Tree: Improving on the Accuracy and Running Time of Decision Trees and Random Forests
Jonathan Bodine

Decision trees are a widely used method for classification, both alone and as the building blocks of multiple different ensemble learning methods. The Max-Cut decision tree involves novel modifications to a standard, baseline model of classification decision tree, precisely CART Gini. One modification involves an alternative splitting metric, Maximum Cut, which is based on maximizing the distance between all pairs of observations that belong to separate classes and separate sides of the threshold value. The other modification is to select the decision feature from a linear combination of the input features constructed using Principal Component Analysis (PCA) locally at each node. Our experiments show that this node-based, localized PCA with the novel splitting modification can dramatically improve classification, while also significantly decreasing computational time compared to the baseline decision tree. Moreover, our results are most significant when evaluated on data sets with higher dimensions, or more classes. For the example data set CIFAR-100, the modifications enabled a 49% improvement in accuracy, relative to CART Gini, while reducing CPU time by 94% for comparable implementations. These introduced modifications are expected to dramatically advance the capabilities of decision trees for difficult classification tasks. The benefits of using the Max-Cut Decision trees are demonstrated to extend to random forests as shown in synthetic experimentation to date.

2 - A k-means algorithm for clustering with hard and soft must-link and cannot-link constraints
Philipp Baumann, Dorit Hochbaum

Constrained clustering is a form of semi-supervised machine learning where the clustering process is guided by domain knowledge. The domain knowledge is often given in the form of pairwise constraints which state that two objects belong to the same cluster (must-link constraint) or to different clusters (cannot-link constraint). State-of-the-art algorithms for clustering with must-link and cannot-link constraints either treat all constraints as hard constraints that must be satisfied or as soft constraints that can be violated with a penalty. We propose a variant of the k-means algorithm which considers simultaneously hard and soft constraints and accepts constraint-specific penalty values for the soft constraints. This flexibility is useful to account for different levels of confidence in the domain knowledge. A methodological feature of the proposed algorithm is a model size reduction technique based on kd-trees that considerably reduces running time. In a computational experiment, we compare the proposed algorithm to state-of-the-art benchmark algorithms on real-world problem instances from the literature. The proposed algorithm consistently outperforms the benchmark approaches in terms of clustering accuracy and running time. Moreover, we show that it is highly beneficial to use constraint-specific penalty values when confidence values are available for the must-link and cannot-link constraints.

3 - Sparse Random Forests via Mathematical Optimization
Kseniia Kurishchenko, Emilio Carrizosa, Dolores Romero Morales

Classification and Regression Trees are powerful tools in Machine Learning since they tend to provide a good accuracy, while they are attractive for non-experienced users because of their visual appeal. Higher accuracy is obtained when different trees are combined, as done e.g. in Random Forests or XGBoost. This is at the expense of a strong loss in interpretability because many trees are involved with no direct control on how many features are used. In this paper, we investigate how to make ensemble tree methods more interpretable by making them sparser (they use overall fewer features). We are given an ensemble of decision trees, where in order to restrict the number of used features some of the trees can be eliminated and the remaining trees are reweighted if needed. Thus, we want to control the accuracy of the ensemble and its sparsity as well. We formulate this as two bi-objective mathematical optimization models, one for the classification task and one for the regression one. The bi-objective model consists of two terms, namely the first term minimizes the loss function and the second one relates to the sparsity. We illustrate the proposed models on a collection of well-known real-world datasets.

4 - Predicting Personal Spending Targets for Promotional Offers
Buse Mert, Defne Eskiocak, Işıl Öztürk

We study a target prediction problem for an FMCG retailer to increase customer participation and engagement for customized promotion offers. We aim to offer the most suitable promotions to customers to provide financial gain and to increase the customer satisfaction. The proposed approach relies on existing personalized promotion offers generated by machine learning. The existing model is used for selecting personalized product categories for promotional offers. In this second phase, we determine customers' spending targets on the selected categories. Currently, these spending goals are produced with a rule-based system. Customers' behavior can change rapidly due to various and unpredictable reasons such as lifestyle changes or Covid-19. Rule-based systems cannot reflect these changes quickly enough. Therefore, we produce predictions that will quickly reflect the change in customer behavior using machine learning methods. We use customers' transactions to produce customer and category-based features. The transactional data covers 12 months for training. We use Random Forest Regressor to create our model. We present our computational results.

■ TA-15

Thursday, 9:00-10:20 - Silberhorn

Project scheduling

Stream: Project Management and Scheduling
Invited session
Chair: *Maximilian Schiffer*

1 - Generation and Characterization of Real-World Instances for the Flexible Resource-Constrained Multi-Project Scheduling Problem
Hendrik Weber, Robert Brachmann, Rainer Kolisch

The Resource-Constrained Project Scheduling Problem (RCPSP) is a well-known and extensively studied scheduling problem. A recent extension is the Flexible Resource-Constrained Multi-Project Scheduling Problem (FRCMPSP) where a portfolio of projects has to be scheduled subject to precedence constraints, scarce resources and resource profile constraints, such that the total weighted lateness is minimized. This paper presents a set of real-world instances for the FRCMPSP based on data gathered from a mid-sized Engineer-to-Order company. We systematically varied these instances in terms of resource availability, due date tightness, and resource demand flexibility leading to a set of 360 instances. In a computational study, we classify the instances according to multi-project characteristics from the literature. Furthermore, we report on solutions and lower bounds obtained with a mixed-integer program and a commercial solver.

2 - A time-based schedule-generation scheme for project scheduling with storage resources and generalized precedence relations
Mario Sillus, Christoph Schwindt

Storage resources represent material stocks or liquid funds that are depleted and replenished at the occurrence of certain events during the execution of a project. Both renewable and nonrenewable resources are special cases of storage resources. Project scheduling subject to storage-resource constraints and generalized precedence relations consists in sequencing the project events in such a way that the inventory levels of the storage resources evolve within given bounds and prescribed minimum and maximum time lags between the events are met. Such a scheduling problem arises, for example, in production planning when material-availability or storage-capacity constraints for intermediate products must be observed or in large-scale projects where cash in- and outflows need be coordinated to avoid liquidity crunches. In presence of storage resources, even the feasibility variant of the scheduling problem is NP-hard. In literature, different enumeration schemes for project scheduling problems with storage resources and regular objective functions like the project duration have been devised. In this paper, we present a new time-based schedule-generation scheme that is intended to serve as a building block for metaheuristic schedule-improvement procedures. The method decodes an event list into a feasible schedule by iteratively resolving resource conflicts. An inventory shortfall or excess is stepwise reduced by increasing or decreasing lower bounds on the occurrence times of appropriate events. We show that the generation scheme is complete and that equipped with some pinch of randomness and unlimited computation time, it is guaranteed to provide a feasible schedule in a single pass. We report on some preliminary computational results obtained on standard data sets.

3 - Scheduling projects with converging and diverging material flows using IBM ILOG CP Optimizer - an experimental performance analysis
Marco Gehring, Rebekka Volk, Niklas Braun, Frank Schultmann

We study the problem of scheduling a construction or deconstruction project subject to precedence and renewable resource constraints so that the makespan is minimized. Moreover, we take into account material flows between activities of the project. Material flows can cause delays due to a limited capacity of intermediate storage facilities. In construction projects, material flows mainly follow a convergent structure, as materials are supplied, pre-treated and mounted over the course of the project. In deconstruction projects, materials are released, treated and removed from the site which results in a divergent structure. Most of the scheduling literature involving material flows and storage facilities address production planning settings where materials are usually regarded as a homogeneous resource which can be consumed by any activity requiring it as soon as enough material is available. In contrast, material flows in (de-)construction projects implicitly prescribe a precedence order on the activities involved. Thus, the structure of the material flows (i.e. convergent or divergent) may have an impact on the tractability of the problem, which we investigate in our contribution. To this end, we systematically generate instances of the problem under various input parameters. We use these instances for a computational performance analysis with IBM ILOG CP Optimizer as solution method - a well-known and state-of-the-art constraint programming solver. The results of this analysis which has not been conducted in the literature so far, provide an insight into further research perspectives in this field.

4 - A New Branch-and-Cut Algorithm for the Rotating Workforce Scheduling Problem
Tristan Becker, Maximilian Schiffer, Grit Walther

Rotating workforce scheduling remains a central planning task in many industries as efficient staff scheduling can ensure a consistent and fair work schedule for employees. Against this background, we propose a new branch-and-cut algorithm for the rotating workforce scheduling problem. We develop a graph representation that allows modeling a schedule as an Eulerian cycle of stints, which we then use to derive a compact problem formulation in terms of the number of employees. Our general branch-and-cut framework solves rotating workforce scheduling in its basic variant and several additional problem variants relevant in practice. These variants comprise maximizing the number of free weekends, minimizing the number of employees, ensuring a minimum number of weekly rest periods, and finding multiple schedules. Our computational studies show that the developed framework constitutes a new state of the art for rotating workforce scheduling. For the first time, we solve all 6000 instances of the status quo benchmark for rotating workforce scheduling to optimality with average computational times of 0.07 seconds and a maximum computational time of 2.53 seconds. These results improve upon the computational performance of existing methods by orders of magnitude. Our algorithmic framework is robust and shows consistent computational performance across all studied problem variants.

■ TA-16

Thursday, 9:00-10:20 - Schilthorn

Scheduling in Health Care

Stream: Health Care Management
Invited session
Chair: *Patrick Hirsch*
Chair: *Fermin Mallor*

1 - Optimization of Physician Schedules at a Department of Internal Medicine
Clemens Thielen, Jan Boeckmann

Physician scheduling is an important task within personnel planning in hospitals and has a large impact both on the efficient operation of the hospital and on employee satisfaction. Good schedules should not only satisfy many complex constraints resulting, e.g., from minimum rest times or required staffing levels, but also achieve a fair distribution of the workload and adhere to the preferences of the planned personnel.

This talk presents a practical physician scheduling problem faced at a medium-sized department of internal medicine of a German hospital as well as an integer-programming-based solution approach for this problem. The problem consists of assigning shifts to physicians both within the normal wards of the department as well as on the intensive care unit (ICU) and the chest pain unit (CPU) over a planning horizon of four to eight weeks. We present the structure of this physician scheduling problem as well as the projected practical implementation of an integer-programming-based solution approach, which uses a web interface to collect all necessary input data and display the computed schedules.

2 - Annual rostering management, with part-time agents and replacement days

David Baez, Odile Bellenguez, Christelle Guéret

This paper deals with a case-study of workforce management in a French hospital. Each service has to face a complex decision-process, dealing with different types of agent contracts. A first phase addresses the strategic workforce allocation to cover shift requirements on a yearly-basis. We propose here a MIP to manage this problem, taking into account the work time and cost of each type of contract. Some additional constraints impose minimum and maximum percentages of part-time staff. The aim is to cover the global care requirements, while minimizing the cost.

A second step is dedicated to establish a cyclic roster of several weeks that will be repeated throughout the year. This roster is built to cover the day-to-day requirements with respect to the different work contracts and work regulations, and has to include a dummy shift that will be used during the operational phase to replace an agent asking for vacation. We introduce here a second model that ensures a good dispatching of the replacement days and their flexibility, under some additional constraints dedicated to practical organization needs. These criteria are important for the final decision-maker who must establish a monthly schedule, using these replacement days to include vacations.

This study shows that some cyclic roster may be impossible to draw or difficult to use, due to an inadequate workforce composition, leading to non-regulatory plannings. Thus, we propose some additional constraints to add in the first MIP, in order to avoid unfeasible composition and enforce a minimum equity between contracts. Results on real-case and randomly generated instances will be shown to evaluate the way regulation expectations are met.

3 - Robust Appointment Scheduling with Waiting Time Constraints

Carolin Bauerhenne, Rainer Kolisch

We present a robust modelling approach to the single-day appointment scheduling problem, where appointment start times on a single server are assigned to a given set of customers with uncertain service times and no-show probabilities. Current approaches minimize a weighted sum of server idle time, customer waiting time, and server overtime. By contrast, we minimize server idle time while providing for each customer a maximum waiting time guarantee. We model the problem using a robust optimization approach with box uncertainty sets, present closed-form optimal solutions for different scenarios and derive easy-to-implement scheduling rules. We show that, in an optimal solution, each customer is scheduled at the earliest possible time while respecting the worst-case waiting time constraints. If there are no-shows, customers are scheduled in the order of increasing service interval lengths. Using simulation, we show that compared to existing robust approaches, our approach significantly reduces idle time, for the worst-case and on average.

4 - Scheduling opening hours in rural healthcare facilities with mobile resources support

Cristina Azcarate, Fermin Mallor, Daniel García de Vicuña, Marta Cildoz, Martín Gastón-Romeo, Laura Frías-Paredes

Healthcare managers are challenged with providing and planning rural services upon the current context of changes in demographic, in communication networks and of new ways of providing healthcare (medicalized ambulances, helicopters, etc.).

In this work we address the problem of reorganizing the continuous and urgent healthcare resources in rural areas. We consider an existing service network organization and we propose an optimization model to determine the geographic location and opening hours of the fixed care centers with the support of mobile resources (ambulances), with the double aim of providing a quality care while keeping the cost at minimum. The model rationalizes the scarce resources as well as guaranteeing quality criteria measured by patient travel times and balancing the workload of the fixed centers.

We propose an integer lineal optimization model that extends classic location problems by integrating time-dependent demand and both fixed and mobile resources.

This model has been applied to the current rural healthcare network in a region of Spain.

Thursday, 10:40-12:00

■ TB-04

Thursday, 10:40-12:00 - Eiger

Algorithms for Discrete Optimization Problems

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Clemens Thielen*

1 - Efficient Algorithms for Multi-Threaded Interval Scheduling with Machine Availabilities
Mariia Anapolska, Christina Büsing, Tabea Krabs, Tobias Mömke

In the Multithread Interval Scheduling with Machine Availabilities (MISMA), each machine has a continuous availability interval and an integer capacity. Furthermore, every job has a fixed processing time interval, during which it occupies one unit of machine capacity. The objective is to assign every job to a machine or to decide that there is no such schedule. In cases when all available machines are equivalent, Flexible Multithread Interval Scheduling with Machine Availabilities (Flex-MISMA) is of practical importance. In Flex-MISMA, all machines have equal capacity, and the ends of their availability periods can be permuted, thus allowing more flexibility for scheduling. Both problems generalize the NP-hard Interval Scheduling with Machine Availabilities, also known as the k-Track Assignment problem. In this paper, we show the strong NP-hardness of both MISMA and Flex-MISMA, in particular already for instances with all machines having capacity of two and for instances with three machines. We establish the relation of the two problems to the Disjoint Paths problem, already known for ISMA. For the remaining cases for Flex-MISMA, i.e. for instances (i) with two machines, (ii) with all machines having unit capacity, and (iii) with a fixed number of machines with fixed capacity, we present polynomial time algorithms. In case (i), we find a special polynomially solvable case of the Disjoint Paths for two pairs of terminal nodes.

2 - Segmentation and repetitive scheduling of linear continuous construction projects
Michael Moos, Sebastian Velten, Christian Weiß

During the planning phase of many large building projects, there is usually an early stage where decisions are made about structuring of the construction activities and division of work amongst project participants. The planner (or, usually, committee of planners) has to split up and structure necessary construction steps into work packages, which are then handed off to subcontractors. We examine a structuring and scheduling problem arising in linear repetitive projects which can be found in the area of, e.g., highway construction. The tasks are performed consecutively along an elongated construction site which can be split into segments. This leads to a repetitive project scheduling problem where the same tasks are performed in a repetitive way in every segment. The segmentation may be different for each individual task. We focus on two major problems: the first is the partition of work amongst subcontractors, including how many subcontractors to hire; the second is the splitting of tasks into smaller ones (according to given rules). Splitting up tasks can be useful, as it may allow more parallelization as well as earlier starting times of task segments. However, it may also be disadvantageous since the splitting of tasks result in more coordination effort. The goal is to optimize the tradeoff between the project's makespan and total cost. We develop a constraint programming model and use it to compute the front of pareto optimal solutions.

3 - An Approximation Algorithm for Interdicting Network Flows with Unit Arc Costs
Jan Boeckmann, Clemens Thielen

In the network flow interdiction problem (NFI), an interdictor aims to remove arcs of total cost at most a given budget from a graph with given arc costs and capacities such that the value of a maximum flow from a source to a sink is minimized. This problem is known to be strongly NP-hard, but - despite its broad applicability - only few polynomial-time approximation algorithms have been found so far. We present a polynomial-time approximation algorithm for the special case of NFI where all arcs have unit removal costs. To the best of our knowledge, this is the first algorithm for a version of NFI whose approximation ratio only depends on the interdiction budget. On simple graphs, its approximation ratio dominates the previously best known approximation ratio.

4 - Some discrete optimization problems in matching markets
Yuri Faenza

In the classical stable marriage problem, we are given two sets of agents - students and schools - with each student and school having a total order of agents from the opposite set. The goal is to form disjoint pairs of students and schools so that the resulting matching satisfies a fairness property known as stability. In their fundamental work, Gale and Shapley showed that a stable matching always exists, and gave a fast algorithm to find one. These strong structural and algorithmic results propelled the application of the stable marriage model in several contexts, most notably for assigning students to public high schools in many cities in the United States.

Although very successful, the marriage model however fails to capture features that have become of crucial importance both inside and outside academia, such as diversity in school cohorts, complex preference patterns, and the need to obtain larger, possibly mildly unstable, matchings. In this talk, I will present some extensions of the concept of stability and of the marriage model, and investigate them from an optimizer's viewpoint.

■ TB-05

Thursday, 10:40-12:00 - Mönch

Multi-Objective and Combinatorial Optimization

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Kathrin Klamroth*

1 - The knapsack problem with special neighbor constraints on directed co-graphs
Steffen Goebbels, Frank Gurski, Dominique Komander

The knapsack problem is one of the best known and most fundamental NP-hard problems in combinatorial optimization. We consider two knapsack problems which contain additional constraints in the form of directed graphs whose vertex set corresponds to the item set. In the 1-neighbor knapsack problem, an item can be chosen only if at least one of its neighbors is chosen. In the all-neighbors knapsack problem, an item can be chosen only if all of its neighbors are chosen. For both problems we consider uniform and general profits and weights. Since all these problems generalize the knapsack problem, they are NP-hard. This motivates us to consider the problem on special graph classes. Therefore, we restrict these problems to directed co-graphs, i.e., directed complement reducible graphs, that are precisely those digraphs which can be defined from the single vertex graph by applying the disjoint union, order and series composition. We show polynomial time solutions for the uniform problems on directed co-graphs and pseudo-polynomial time solutions for the general problems on directed co-graphs. These results improve known worst-case runtimes in comparison to constraints given by unrestricted digraphs.

2 - A new label setting framework for the Multiobjective Shortest Path problem
Pedro Maristany de las Casas, Ralf Borndörfer, Antonio Sedeño-Noda

In this talk we will discuss a new algorithmic framework for the Multiobjective Shortest Path (MOSP) problem. In this problem, each arc in the input graph bears more than just one cost attribute as opposed to the well known Shortest Path problem in which scalar costs are defined on the arcs and thus, on the paths. Hence, in the MOSP problem, the costs of a path are represented by a vector of the attributes collected along its arcs and the optimality among paths has to be redefined. The commonly used Pareto dominance on the set of feasible cost vectors gives raise to a possibly exponential number of optimal paths in general. Not only MOSP problems are known to be intractable, it has also been shown that they are NP-hard. Still, particularly in the biobjective case, MOSP problems are often solved in practice and in the literature.

The complexity analysis of the used algorithms is often skipped and when presented, their running time bounds exhibit a quadratic dependency on the possibly exponential output size. We present the Multiobjective Dijkstra Algorithm (MDA), a new MOSP algorithm with a much better complexity bound that also exhibits its superiority in the extensive computational results that we made. Of course, the intrinsic difficulty of having a possibly exponential number of solutions is still existent and thus, finding a polynomially sized subset that is emphgood enough is an attractive goal. We will show how the Pareto dominance relationship can be modified to get a multiobjective FPTAS for MOSP problems. The FPTAS is based on the MDA and performs well in theory and practice.

3 - Biobjective Optimization Problems on Matroids with Binary Costs
Julia Sudhoff, Jochen Gorski, Kathrin Klamroth

Like most multiobjective combinatorial optimization problems, biobjective optimization problems on matroids are in general NP-hard and intractable. In this talk, we consider biobjective optimization problems on matroids where one of the objective functions is restricted to binary cost coefficients. We show that in this case the problem has a connected efficient set with respect to a natural definition of a neighborhood structure and hence, can be solved efficiently using a neighborhood search approach. This is, to the best of our knowledge, the first non-trivial problem on matroids where connectedness of the efficient set can be established.

The theoretical results are validated at extensive numerical experiments with biobjective minimum spanning tree problems (graphic matroids) and with biobjective knapsack problems with a cardinality constraint (uniform matroids). In the context of the minimum spanning tree problem, coloring all edges with cost 0 green and all edges with cost 1 red leads to an equivalent problem where we want to simultaneously minimize one general objective and the number of red edges (which defines the second objective) in a Pareto sense.

4 - Efficient Scalarization-based Methods for Multiobjective Integer Programming
Kathrin Klamroth, Kerstin Daechert, Tino Fleuren

In this talk, we present an efficient and easily implementable method for the exact solution of multiobjective integer programming problems (MOIPs) with an arbitrary number of objective functions. This generic scalarization-based approach is based on the iterative solution of single-objective integer programs (IPs) and thus benefits from the strength of single-objective IP solvers. We present numerical results comparing overall solution times with several state-of-the-art objective space methods in order to analyze the trade-off between the required number of solver calls on one hand and their complexity on the other hand, i.e., the difficulty of the scalarized subproblems. Besides the evaluation of knapsack and assignment instances from the literature, we also present new instances with up to 10 objectives. The results show that the generic algorithm outperforms existing methods considerably. For the new high dimensional instances it is even sometimes the only method that can compute the nondominated set, even when giving the other methods a ten times longer runtime.

■ TB-06

Thursday, 10:40-12:00 - Jungfrau

Two-Stage Stochastic Optimization

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Steffen Rebennack*

1 - Utilizing strengthened lift-and-project cuts in decomposition methods to solve two-stage stochastic programming problems with binary first-stage variables
Pavlo Glushko, Achim Koberstein, Csaba Fabian

Lift-and-project cuts are well-known general 0-1 programming cuts which are typically deployed in branch-and-bound-type methods to solve MILP problems. In this talk, we discuss ways to use these cuts in Benders' type decomposition algorithms for solving two-stage stochastic programming problems with binary first-stage variables. In particular, we show how L&P cuts derived for the mixed-binary first-stage master problem can be strengthened by utilizing second-stage information. We present an adapted L-shaped algorithm and some computational results.

2 - A Risk Averse Formulation for Bilevel Problems under Stochastic Uncertainty
Johanna Burtscheidt, Matthias Claus

Stochastic bilevel problems arise from the interplay between two decision makers on different levels of hierarchy where the lower level problem is entered by a random vector. In our context, this models production errors of a shape or truss that has to be optimized due to possible acting forces. We present a deterministic formulation for a bilevel problem under stochastic uncertainty which is based on special risk measures. In particular, structural properties and qualitative stability of the optimal value function of this model will be investigated.

3 - Optimality Conditions in Risk-Neutral Bilevel Stochastic Linear Programming
Matthias Claus, Johanna Burtscheidt, Stephan Dempe

We consider risk-neutral bilevel stochastic linear programs with random lower level right-hand side, examine analytical traits of the arising expectation functional and provide optimality conditions in terms of generalized Hessians.

4 - A converging Benders' decomposition algorithm for two-stage mixed-integer recourse models
Niels van der Laan, Ward Romeijnders

We propose a new solution method for two-stage mixed-integer recourse models. In contrast to existing approaches, we can handle general mixed-integer variables in both stages, and thus, e.g., do not require that the first-stage variables are binary. Our solution method is a Benders' decomposition, in which we iteratively construct tighter approximations of the expected second-stage cost function using a new family of optimality cuts. We derive these optimality cuts by parametrically solving extended formulations of the second-stage problems using deterministic mixed-integer programming techniques. We establish convergence by proving that the optimality cuts recover the convex envelope of the expected second-stage cost function. Finally, we demonstrate the potential of our approach by conducting numerical experiments on several investment planning and capacity expansion problems.

■ TB-07

Thursday, 10:40-12:00 - Niesen

Heuristics for industrial applications

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *Alberto Locatelli*

1 - Heuristic approach to a real-world two-stage flexible flow shop problem with workers allocation
Beatrice Bolsi, Vinícius Loti de Lima, Thiago Alves de Queiroz, Manuel Iori

We study an optimization problem which is faced daily by meat industries and other manufacturing companies as well. In our case study, a set of orders have to be produced by following two stages: in the first stage, the meat is processed (cut) on a given bench, and in the second stage it is sent to a conveyor to be packed into disposable trays. Benches and conveyors are seen as heterogeneous parallel machines, and their productivity depends on the number of workers operating each. The problem has many practical constraints: orders have release and due dates, as well as a maximum waiting-time and a transportation time between the first and second stage; orders are organized into families causing family-related setups on the machines; a work-day is divided into up to two shifts, each characterized by time-related constraints. The decisions involve the total number of workers needed on each period, their distribution on the machines, and the sequencing of the orders. The problem has a lexicographic function based on the minimization of the number of tardy jobs, the number of setups, and the total production cost. To efficiently solve the problem, we propose a multi-start random constructive heuristic that: (i) sorts the orders at random; (ii) considers different allocations of workers to machines; and (iii) schedules the orders in the first and second stages by following a list of priorities. Extensive computational tests prove the effectiveness of the proposed solution method.

2 - Scheduling of parallel print machines with sequence-dependent set-up costs: A real case study

Alberto Locatelli, Manuel Iori, Marco Locatelli

In the present work, we consider a real-world scheduling problem arising in the color printing industry. The problem consists in assigning print jobs to flexographic printer machines, as well as in finding a processing sequence for the sets of jobs assigned to each printer in order to minimize total tardiness and total setup times. All the considered machines are characterized by a limited sequence of color groups and can equip additional components (e.g., embossing rollers and perforating rolls), if a job requires specific treatments. A job is characterized by a sequence of colors and, during its print, each color takes exactly a color group, respecting a specific chromatic order. The process to equip a machine with an additional component or to clean a color group takes a long time with the effect of significantly raising of the set-up costs. Furthermore, the time required to clean a color group between two different jobs depends directly on the involved colors. If the two colors are similar, it is sufficient just a fast and partial cleaning of the color group, otherwise the cleaning operation has to be complete. To tackle this problem, we propose a constructive heuristic and several local search methods used in a iterative way. Finally, the heuristics are tested on real instances in order to show that the proposed methods are able to lead to good solutions in a short amount of time.

3 - Skill-Based Joint Order Batching and Picker Routing Problem

Jafar Jamal, Andrea Di Florio Di Renzo, Dominic Loske, Matthias Klumpp, Xiaochen Chou, Roberto Montemanni

In the last few years online sales have increased significantly and as a result, warehouses have diversified they mission, now playing an important role both in a traditional supply chain and in an e-commerce one. Consequently, the work in warehouses needs to be improved and simplified, both for companies, that need to increase efficiency, and especially for human workers who have seen their jobs becoming more and more stressful and tiresome. This in turn has negative impacts on process and logistics performance.

The problem of batching orders and routing orders in picker-to-parts warehouses is intensively studied in the research literature, but the impact of individual differences among pickers or forklift operators and their skills are rarely taken into consideration. Therefore, we propose a model that does simultaneously order batching and routing while taking advantage of single worker's skills. This approach allows to optimize the total batch execution time, which is useful for the company. At the same time it reduces workers' physical and mental effort since they are likely to perform tasks within their capability sphere and motivational preferences, since their profiles indicate they execute them easily.

4 - Iterated Local Search for the Technician Routing and Scheduling Problem

Ala-Eddine Yahiaoui, Hamid Allaoui, Sohaib Lafifi

In this presentation, we consider a variant of the Technician Routing and Scheduling Problem. Given a limited crew of technicians and a set of tasks to be performed at their respective locations, the goal is to assign tasks to individual technicians and construct the routes for each technician so that the total duration is minimized. Several types of constraints have to be respected in each route. The first type of constraints is compatibility constraints, where, each task requires the proficiency in a specific set of skills from the assigned technician, whereas some technicians have not necessarily the proficiency of all those skills. The second type of constraints are resource requirements, where each task requires a certain amount of several resources of different types. Two major classes of resources are considered: tools and spare parts. Each technician starts its route from its home depot with a set of tools and an initial inventory of spare parts of different types. In case where a technician does not have the required tools and/or spare parts, it has the opportunity to acquire them by visiting a central depot once at some point in the route. We assume that an infinite stock of tools and spare parts are available at the central depot. Finally, each task must be performed within a predefined time window. For this problem, we proposed a new mathematical model that is used to solve small-size instances. For large-size instances, we proposed an Iterated Local Search method enhanced by a set of local search operators designed specifically for the problem. Computational tests have been carried out on benchmark instances from the literature. Preliminary results show the good performance of our method compared with the existing method in the literature.

■ TB-08

Thursday, 10:40-12:00 - Stockhorn

GOR award presentation and presentations about system boundaries

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

1 - A Branch-and-Price algorithm for the electric freight vehicle scheduling problem

Patrick Klein

Electric Commercial Vehicles (ECVs) constitute a promising alternative to conventional internal combustion engine vehicles as they allow for (locally) emission-free operations and may reveal economic benefits resulting from low operational cost. However, realizing economically worthwhile ECV operation remains challenging as often sparse charging infrastructure and long recharging times limit recharging operations to the depot. Here, ahead of time scheduling is necessary to guarantee charger availability. Potential cost savings through time-varying energy prices and deaccelerated battery degradation further complicate this planning problem. This talk formalizes and solves the arising scheduling problem. For this purpose, we model the problem on a time-expanded network and develop an exact branch and price algorithm based on a set partitioning formulation. The pricing problems constitute an extension to the fixed-route vehicle charging problem, introducing time windows and energy cost. We propose a labeling algorithm to solve the resulting shortest path problem. Our approach outperforms state-of-the-art integer programming solvers on a large set of benchmark instances. We further assess the impact of specific instance parameters, e.g., fleet size, planning horizon length, on our algorithm's performance. Our study confirms the scalability of our algorithm. Finally, we show the impact of depot charge scheduling on a fleet operator's overall cost for realistic instances.

2 - Expanding conventional energy system models with material flows and production processes

Michel Obrist

Current techno-economic bottom-up energy system optimization models based on the TIMES (The Integrated MARKAL-EFOM System) modeling framework are mainly focused on energy and emission flows. However, for a more detailed analysis of the industrial sector in energy system models, it is essential to connect the energy consumption to the specific production processes and material flows. The present research paper presents an advanced modeling methodology to include production processes with all relevant material flows in addition to the conventional energy flows into an energy economic modeling framework. This methodology allows to analyze process-, energy- and material-efficiency improvements and emission mitigation options of single process steps as well as of the entire production process. Furthermore, it enables the option to include process related CO_2 emissions from chemical conversion in addition to energy related emissions from fuel combustion. This leads to a more elaborated analysis of the energy consumption and the CO_2 emissions from the industrial sector. The modelling methodology is ultimately applied in a full-scale scenario analysis to investigate long-term energy consumption and CO_2 emission mitigation pathways of the Swiss industry with the Swiss TIMES Energy system Model (STEM). With the advanced methodology, the model contributes to an improved understanding of energy technology development and identifies policy strategies for the realization of a decarbonized Swiss industry.

3 - Measuring the quality of decision rules for dynamic multi-criterial sequential problems in a dynamic environment: a Simulation Study

Martin Romauch, Selim Erol, Jakob Kühnen

Traditional objectives considered in operations management and especially in transport logistics are e.g. cost reduction, delivery date adherence, delivery failure reduction, inventory minimization. Though, recent efforts on the policy level, regarding decarbonization of transport, need additional objectives to be considered, e.g. reduction of emissions. These objectives need to be continuously considered in strategic, tactical and operational decisions (Besiou and van Wassenhove, 2015). Although several multi-criteria decision methods have been found suitable to solve isolated problems, little work has been done to tackle stochasticity stochasticity of the input data and long-term effects at the same time (Kandakoglu et al., 2019). One way to address long-term effects, is to combine multi-objective sequential programs and sensitivity analysis or to integrate stochastic elements in the model (stochastic programming, SSA). For multi-stage problems, with stochastic parameters or incomplete information, it is hard to find decompositions into smaller tractable subproblems, hence simulation seems to be a suitable alternative to exact approaches (Grötschel et al., 2013). In this paper we propose a framework to measure the quality of decision rules for a multi-criterial sequential problem in a dynamic environment that encompasses the problems related to the competitive ratio (Hasegawa and Itoh, 2018; Tiedemann et al.). An exemplary case-study of an industrial company is used to evaluate the quality of different heuristics (decision rules) for a multi-stage problem with stochastic demands. The heuristics cover the operational decision and they are guided by a predefined strategic multi-criterial goal. A simulation model implemented with AnyLogic is used for the assessment.

■ TB-09

Thursday, 10:40-12:00 - Gantrisch

Multi-Criteria Decision Support for Energy Transitions

Stream: Energy and Environment
Invited session
Chair: *Valentin Bertsch*

1 - Implementing the augmented epsilon-constraint method for multi-objective energy systems optimisation

Jonas Finke, Valentin Bertsch

Anthropogenic climate change has disastrous consequences for people and ecosystems. To mitigate these consequences, global efforts are undertaken to transform energy systems towards a more sustainable future based on renewable energy sources. With this transformation, greenhouse gas emissions and environmental sustainability become more important objectives. More stakeholders with diverse and partly conflicting interest enter the increasingly decentralised sector. Energy system models support decision making by providing analyses and insights to the sector and its transformation. Optimising energy systems for multiple objectives simultaneously rather than, as often done, costs only explores the range of and trade-offs between different Pareto-optimal scenarios. We present a further development of the highly adaptable open source energy systems optimisation framework Backbone. In Backbone, multiple energy sectors can be optimised for minimal costs at any desired temporal and spatial resolution while taking into account operational and reserve constraints as well as stochastic behaviour. New features allow to, first, minimise for emissions instead of costs and, second, obtain elements of the cost-emission Pareto front by using the AUGMECON method. A new algorithm calls Backbone to obtain boundaries of the 2D objective space by minimising costs only and emissions only. It then calls the Backbone AUGMECON implementation multiple times in parallel to obtain a representative subset of the Pareto front. A case study examines optimal generation and storage investments in the European power sector, comparing scenarios towards zero emissions. Future work will integrate additional environmental and social impacts in multi-objective optimisations of energy systems.

2 - Electricity system expansion planning of the Rhenish Mining Area considering environmental impacts by using multi-criteria-optimization

Sophie Pathe, Valentin Bertsch

In the context of climate change and the increasing demand for sustainable solutions in the energy sector, it is of particular interest to consider environmental impacts in energy system analyses. The consideration of CO2-emissions is quite common, whereas other environmental impacts are often neglected. However, many other impacts are highly relevant, too, especially given that for renewable energies, the environmental impacts shift towards other impact categories, e.g. the consumption of certain metals. Impacts also shift from the use phase to the production phase. This requires a multi-objective optimisation of energy systems, considering not only techno-economic, but also environmental and/ or societal aspects.

Using the energy system model Backbone, the German electricity system is analysed with special consideration of the Rhenish Mining Area (RMA). This area is of particular interest since lignite-fired power plants are highly concentrated there, which will be shut down until 2038 which leads to a new structural change in the region. The current state is compared with scenarios after the end of the coal phase-out. This study examines to what extent and under what conditions the replacement of lignite-fired power plants takes place within the RMA. In addition to costs, CO2-emissions and the consumption of certain resources are included in the optimisation, not only as boundary conditions but as objective functions. Through this multi-criteria optimisation, insights can be gained into the interrelationships of the various target variables and their effects on the optimal solutions. The augmented epsilon-constraint method AUGMECON is used to determine pareto-optimal solutions.

3 - Computational improvements to generate spatially-explicit alternatives for renewable capacity deployment (TurboSPORES)

Francesco Lombardi, Brynmor Pickering, Stefan Pfenninger

Operations research is used to support large-scale capacity expansion planning in the context of the energy transition, most typically in the form of cost-minimising linear programming models. However, cost-optimality is often not the goal, or only one of many competing goals, in real-world planning. In recent work, we developed the SPORES method to generate spatially explicit near-optimal solutions. Previous near-optimal solution methods were unable to generate spatially diverse model results, while our method focuses explicitly on siting generation capacity on the sub-national scale, which is also where many competing objectives matter most, such as mitigating local landscape impacts. However, applying our method at the spatial resolution required by real-life decision-making structures means modelling hundreds of sub-national locations, leading to a trade-off with respect to computational tractability. Here we develop and empirically test several improved mathematical formulations that maximise the diversity of our near-optimal results, including formulations adapted from methods proposed in the literature. We compare and critically discuss the benefits and limitations of each, thereby providing generally applicable insights around how to best use limited computational capacity to generate the most diverse set of near-optimal alternatives without redundant computation.

4 - Ecological optimization of the charge of battery electric vehicles

Leon Zacharopoulos, Jutta Geldermann, Nils Thonemann, Marcel Dumeier

Battery electric vehicles (BEVs) are an important element in future scenarios to decarbonize the individual transportation sector. Life Cycle Assessments (LCA) show the high influence of the use phase of BEVs on the CO2-equivalent emissions due to the power supply. These results however are highly uncertain because of the rising share of renewable energy sources for electricity supply. The dynamics can be divided into short-term (e. g. hourly availability of wind and solar power) and long-term (e. g. development of power plant network). In the face of temporal dynamics, the objective of our study is to quantify the minimization potential of the environmental impacts by choosing the optimal point in time for charging BEVs. A mixed-integer linear programming model (MILP) is used to generate charging profiles that minimize the environmental impacts from BEV charging. In the model, representative driving patterns are linked with the environmental impacts of different electricity generation scenarios. A dynamic LCA approach is used to assess the environmental footprint of power generation with an hourly resolution concerning 16 impact categories. The uncertainty due to different power generation scenarios is faced by modeling the power generation for different years up to 2050. Finally, the goal conflicts between the different environmental impact categories (e. g. Global warming, Homan toxicity, Resource depletion) are discussed. This study's results indicate high mitigation potentials provoked by the smart charging approach. Further, the charging profiles for each impact category can be clustered to reduce the conflicting charging profiles by minimizing the BEV's total environmental emissions.

■ TB-10

Thursday, 10:40-12:00 - Schreckhorn

Stochastic & Dynamic problems

Stream: Logistics and Freight Transportation
Invited session
Chair: *Jan Fabian Ehmke*

1 - On the design of crowdsourced delivery fleets: Strategic decisions and operational implications

Julius Luy, Maximilian Schiffer

Crowdsourced deliveries via occasional drivers (OD) is a promising concept to reduce delivery traffic in urban areas by synchronizing delivery requests with trips of private individuals and letting them perform parcel shipments. However, trips of private individuals and their willingness to serve as an OD are stochastic such that they constitute uncertain transport capacities from a logistics service provider's (LSP's) perspective. Accordingly, current research on crowdsourced deliveries with occasional drivers focuses on developing algorithms for operational decision-making under supply uncertainty. Strategic analyses on how to design a delivery fleet partly relying on occasional drivers are still missing, although such fleet composition decisions can have significant operational implications, e.g., w.r.t. service levels. Against this background, we study a novel approach that integrates operational decision-making in the respective fleet composition problem. We consider a mixed driver fleet consisting of occasional drivers, independent contractors, and fixed employees over a multi-period time horizon. Knowing the expected demand levels in upcoming time periods, an LSP decides how to compose her fleet to preserve service level constraints. This decision is, however, affected by an operational driver-to-request assignment problem. To capture this interdependency, we formulate the fleet composition problem as a Markov decision process and embed a stochastic driver-to-request assignment problem to account for the operational level's impact. We conduct a case study based on real-world data to derive optimal fleet composition policies for given demand scenarios and perform sensitivity analyses regarding service level constraints and OD-specific parameters.

2 - Anticipatory decision-making for stochastic dynamic vehicle routing

Ninja Soeffker, Marlin Wolf Ulmer, Dirk Christian Mattfeld

We consider a dynamic vehicle routing problem with stochastic customer requests. While some initial customers requested service in advance of the time horizon and can be scheduled before the vehicles depart from the depot, other customers request service throughout the time horizon when the vehicles are already traveling. For this problem setting, decisions need to be made both about the routing of the initial customers as well as about the acceptance of new customer requests. For the initial routing, we consider different options. For the decisions about the acceptance and routing of new customer requests, we apply value function approximation, a method of approximate dynamic programming. We show the impact of the different initial routing options on the solution quality, analyze the choice of features to be used in the value function approximation, and discuss the relationship between the initial routing and the chosen features.

3 - A machine learning approach for a fleet-based data-driven emissions model

Johann Hillmann, Jan Fabian Ehmke

Road-based freight transportation is responsible for a significant share of emissions such as emitted CO2. In recent years, there have been significant efforts to include detailed emissions models in objective functions of transportation optimization such as vehicle routing models. However, while these models are often more complex than traditional objective functions such as minimizing distances, it is an open question how much they contribute to developing more sustainable route plans. In this work, we compare the quality of emissions models with regard to estimating emissions precisely and planning environmental-friendly routes. Conventional closed-form approaches such as the Comprehensive Modal Emissions Model (CMEM) or the Methodology for Estimating air pollutant Emissions from Transport (MEET) often prove to be too imprecise and static for the task, creating a need for new, enhanced models. To this end, we follow a data-driven approach and develop a more precise, robust, and generalizable emissions model by incorporating fleet-based fuel consumption data together with machine-learning techniques. Experiments are based on publicly available data from vehicles in daily road traffic in the Quebec metropolitan area. We train and evaluate several regression models, e.g. linear regression, polynomial regression, tree ensembles, and neural networks, to infer vehicle fuel consumption from driving characteristics. Our early results show that a data-driven approach outperforms conventional closed-form models. Further, energy-efficient routes may look much different from the fastest routes and can be identified by the model. In the future, the model may be extended by additional parameters relating to vehicle characteristics, environmental variables, or driver behavior.

4 - Dynamic snow ploughing on a rolling horizon basis

Georg Erwin Adrian Fröhlich, Karl Doerner, Margaretha Gansterer

Snow ploughing is a relevant real-world problem that is often studied in a non-urgent, static fashion, where plans are created offline. Research regarding more dynamic versions, such as severe snowstorms that threaten to shut down the whole infrastructure and quickly replenish the amount of snow, are not well studied. We aim to close this gap by focusing on a dynamic model, where a snowstorm is currently taking place and the precise amount of snowfall and its trajectory are not known. Our aim is to keep the street network reasonably secure during the storm. Whether a street segment is deemed secure, is determined by the piled-up snow. For the overall security of the street network, we weigh individual street segments according to the importance (e.g., high weights for main roads, access streets to hospitals). To tackle this, we implement a metaheuristic that is required to deliver good solutions within a limited computation time and adapt to the current state of the system and new data - our method of choice here being ALNS. New plans are created on a rolling horizon basis, using predictions based on the current state and the snowfall, to account for sudden changes. For reducing computational effort on larger instances, we also examine the use of multiple different decomposition techniques. Since our problem characteristics are not fully comparable to other published results, we started by validating our ALNS's efficacy by comparing with classical benchmark instances in the arc routing literature. For our problem itself, we aim to compare online executions of our algorithm with different horizon sizes and decomposition techniques and offline executions with far larger computation time and/or even full information.

■ TB-11

Thursday, 10:40-12:00 - Wildstrubel

Sustainable Finance and Catastrophe Finance

Stream: Finance
Invited session
Chair: *Stefan Kupfer*

1 - The Challenge of CAT Bond Pricing: Random Forests win the Race

Eileen Witowski

The main challenge of empirical asset pricing is the forecast of the future value of assets traded in financial markets at a high level of accuracy. This challenge becomes increasingly important in the (secondary) market for CAT bonds, which is used by investors to trade risks related with the occurrence of natural catastrophes and which has been growing significantly over the past years. Although the theoretical and the empirical literature have devoted a lot of attention to the determinants of CAT bond risk premiums and to their forecast on the primary market, the recurring premium forecast on the secondary market has so far been neglected. Against this background, the goal of the present study is to identify a suitable forecasting model for the CAT bond secondary market. To reach this goal, we consider a comprehensive set of modeling approaches including linear regression, random forests, and neural networks. The considered set of modeling approaches enables us to also capture the potentially non-linear and non-parametric relationships between CAT bond premiums and their determinants. The comparison of the different modeling approaches on a comprehensive data set of CAT bond issues and across various forecasting settings shows that random forests yield the highest forecasting accuracy and the most stable results, followed by linear regression and neural networks. Our results contribute to the empirical asset pricing literature by providing evidence on the performance of different statistical modeling approaches and they are relevant to CAT bond market participants which continuously seek to improve their pricing models.

2 - Statistical Models Based Stock Trading Strategy for Vaccine Development Company during COVID-19 Outbreak
Chi-Feng Ho, Chi-hong Ho

COVID infected more than 100 million people in the world and caused about 3 million deaths. Lots of biotech companies started the vaccine development and published the results in July, and also the US government ordered over 100 million vaccines. Authors bought in 5 of the most potential vaccine company stocks via multivariate statistical models on Aug. 11, and authors planned to start the exchange phase on Nov. 17th. The most important event after the buying phase is the US presidential election. The stock market often reflects the views of the future, thus, the uncertainty of the election results will affect the market. The authors derived the Z-Exchange index by using Z-Standardization. Authors used outlier detection tools to find the best exchange stock pairs. The authors compared three different stock exchange operations to find the best exchange strategy and also validate the market efficiency of Wall Street. The authors established the automated trading systems, which can help eliminate the human factors, and also, finding the best timing. The authors set up some rubrics and checked threshold values to make the auto trade system more useful and accurate.

3 - The Influence of ESG Ratings on Idiosyncratic Stock Risk: The Unrated, the Good, the Bad, and the Sinners
Matthias Horn

This study analyzes two questions. First, do stocks of companies with Environmental Social Governance (ESG) rating show lower idiosyncratic risk? Second, do stocks of ESG-rated companies subject to a negative screen show lower idiosyncratic risk than comparable stocks of ESG-rated companies not subject to a negative screen? The main analysis covers 898,757 company-month observations of US stocks in the period from 1991 to 2018 and controls for stocks' exposure to liquidity, mispricing, innovations in volatility risk, investor sentiment, and analysts' forecast divergence. The main findings are that stocks of companies with an ESG rating show significantly lower idiosyncratic risk than stocks of companies without ESG rating and that stocks subject to a negative screen show lower idiosyncratic risk during recessions and since the last financial crisis than comparable stocks with an ESG rating but without a negative screen. The results support the notion that the receipt of an ESG rating decreases uncertainty regarding future stock risk and return and provides further empirical support for the defensive nature of sin stocks.

4 - Sustainable Investment Timing, Agency, and Information
Stefan Kupfer, Max-Frederik Neubert

To provide an analytical explanation for delayed investments and low commitment to sustainability projects, we analyze a dynamic real option model where a manager (the agent) is responsible for the timing and scaling strategy of investment decisions. There are two types of projects available, one with higher payoff but lower commitment to sustainability, i.e., lower scale (type I), and another with lower payoff but higher sustainability commitment (type II). The owner (principal) employs the manager because he has an informational advantage about project payoffs and a specific reputation in the field of sustainability. A higher reputation increases the expected profitability of the project. However, the manager has career concerns and since he needs to publicly report on the sustainability progress, pressure on the manager increases as well, i.e., he will suffer reputational damage if the commitment to sustainability is not large enough. To design the optimal contract the principal has to incorporate a potential reputation damage compensation into the contract in addition to incentives to provide effort and to disclose private information truthfully. We analyze the owner's trade-off between the costs of the manager's sustainability pressure due to early but low commitment (realization of type I) and lower payoffs in a later but potentially larger investment in sustainability (realization of type II). In contrast to existing literature, we find that higher managerial reputation leads to a strategy change in the type I project, delaying investment and increasing scale. We also show that the owner has to trade-off sustainability contracting costs against project financial performance when choosing a manager with a particular reputation.

■ TB-12

Thursday, 10:40-12:00 - Faulhorn

Dial-a-Ride Problems II

Stream: Mobility and Traffic
Invited session
Chair: *Tai-yu Ma*

1 - Learned Optimization Guidance for Dynamic Dial-a-Ride Problems
Christian Ackermann, Julia Rieck

In the dial-a-ride problem, customers have to be transported from different pickup to drop-off locations, where the corresponding locations are known in advance. Various constraints such as time windows and a maximum travel time per passenger also need to be considered. The optimization goal is typically the minimization of the total distance driven by the given fleet of vehicles. In the dynamic version of the problem, not all customer requests are known in advance, but arrive during the operation time. Therefore, instead of minimizing the distance, the maximization of the number of served customers is usually set as the optimization goal. Nevertheless, in the vast majority of known heuristics, total distance is used to guide the optimization. This is done under the assumption that a more efficient routing of vehicles leads to more available capacity for later arriving customer requests. However, it can be shown that different slack times of the temporary solutions correlate stronger with the final acceptance rate than their distances. Our goal is therefore to replace the currently used distances with a learned estimator for the potential to insert later customers in order to guide both the insertion heuristics as well as the local search more explicit to the best solution. To this end, we propose different metrics for the temporary solutions combined with machine learning models from supervised and reinforcement learning. The experimental performance analysis shows the advantage of our learned optimization guidance for dynamic dial-a-ride problems.

2 - A Learning-Based Optimization Approach for Autonomous Ridesharing: Modeling Service Classes and On-Demand Hiring of Idle Vehicles
Frederik Schulte, Breno Alves Beirigo

With the popularization of transportation network companies (TNCs) (e.g., Uber, Lyft) and the rise of autonomous vehicles (AVs), even major car makers increasingly focus autonomous mobility-on-demand (AMoD) services. Nonetheless, reaching the convenience of owning a vehicle requires consistent service quality (SQ), taking into account individual expectations concerning responsiveness, reliability, and privacy. Planning models presented in the AMoD literature, however, do not enable active control of service quality, sometimes allowing extensive delays and user rejections. In this work, we propose an AMoD system that uses the SQ expectations of heterogeneous user classes to control service quality among riders on an operational planning level. We formalize the problem as the dial-a-ride problem with service quality contracts (DARP-SQC) and propose a multi-objective matheuristic to address real-world requests from Manhattan, New York City. We also propose a learning-based optimization approach that uses the dual variables of the underlying assignment problem to iteratively approximate the marginal value of vehicles at each time and location under different availability settings. These values are used in the objective function of the optimization problem to dispatch, rebalance, and occasionally hire idle third-party vehicles. Applying the proposed service-level constraints, we improve user satisfaction (in terms of reached service-level expectations) by 53% on average compared to conventional ridesharing systems, even without hiring additional vehicles. Moreover, our results show that the proposed learning-based optimization policy outperforms a reactive optimization approach in a variety of vehicle availability scenarios while hiring fewer vehicles.

3 - Optimal queueing-based vehicle charging scheduling and assignment for dynamic electric ridepooling service
Tai-yu Ma, Yumeng Fang

Electrifying electric vehicle fleet for ride-hailing service needs to efficiently manage the daily charging operation to minimize charging waiting times and cost under stochastic customer demand. Given capacitated charging facilities and varying charging prices, the issue of determining where, when, and how much to charge for each vehicle is a challenging issue for successful deployment of e-fleet. In this study, a new two-stage solution approach is proposed to handle dynamic vehicle charging scheduling to minimize the costs of daily charging operations of pooled ride-hailing service. A new vehicle charging scheduling model is proposed to obtain a day-ahead charging schedule for each vehicle based on the historical driving patterns of vehicles. Then an online queueing-based vehicle-charger assignment model is developed to determine where to charge by considering queueing delays at the level of chargers. An efficient Lagrangian relaxation algorithm is proposed to solve the large-scale vehicle-charger assignment problem with small optimality gaps. The approach is applied to a realistic dynamic microtransit service case study in Luxembourg and compared with the nearest charging station charging policy and first-come-first-served minimum charging delay policy under different charging infrastructure scenarios. The computational results show that the approach can achieve significant savings for the operator in terms of charging waiting times, charging times, and charged energy costs.

■ TB-13

Thursday, 10:40-12:00 - Blüemlisalp

Airline Revenue Management & Applications

Stream: Revenue Management
Invited session
Chair: *Thomas Winter*

1 - Customized airline offer management: a conceptual architecture

Daniel Schubert

Revenue management has been a strategic priority for airlines for decades. More recently, ancillary revenues and targeted offers for diverse customers have become increasingly relevant. Hence, airlines need to evolve their revenue management into offer management. This paper designs a modular and conceptual architecture for customized real-time offer management comprising dynamic bundling, ancillary pricing, flight pricing, and assortment. The research reviews existing literature and expands on these in several directions. It applies machine learning for highly granular customer segmentation and develops a new application of the matrix factorization algorithm to overcome resulting data sparsity problems. The architecture aims to increase airline revenues in two ways. First, targeted offers enhance customer satisfaction. Second, more granular willingness-to-pay estimation improves pricing decisions.

2 - Synchronized Dynamic Programming for Simultaneous Control of Several Leg Compartments

Thomas Winter

We consider a problem arising in airline revenue management when a flight leg offers service in different service classes like business class, premium economy and economy class. The corresponding demand includes customer choice options between service and booking classes or different price levels. Typically, the demand is split between the corresponding leg compartments and the optimization of price levels at which the seats shall be sold is carried out independently for each compartment. The coupling of demand between the compartments is usually neglected - or resolved heuristically, very often sub-optimally in a pre-computing step. In our work, we present different dynamic programming approaches for this control problem for several leg compartments. We compare the traditional approach of independent calculation of the compartment dynamic programs to coupled calculation of the dynamic program cores at a predefined subset of the internal decision points. In this context, we also discuss the impact of capacity constraints for service class and possible extensions to network scenarios.

3 - Demand Forecasting in Hospitality Using Smoothed Demand Curves

Rik van Leeuwen, Ger Koole

Forecasting demand is one of the fundamental components of a successful revenue management system in hospitality. The industry requires understandable models that contribute to adaptability by a revenue management department to make data-driven decisions. Data analysis and forecasts prove an essential role for the time until the check-in date, which differs per day of week. This paper aims to provide a new model, which is inspired by cubic smoothing splines, resulting in smooth demand curves per rate class over time until the check-in date. This model regulates the error between data points and a smooth curve, and is therefore able to capture natural guest behavior. The forecast is obtained by solving a linear programming model, which enables the incorporation of industry knowledge in the form of constraints. Using data from a major hotel chain, a lower error and 13.3% more revenue is obtained.

4 - Sustainable product design when durability matters - with applications to the case of electric toothbrushes

David Topchishvili, Cornelia Schoen

In 2012, The Washington Post (Basulto 2012) suggested that Apple, in line with other technological companies, embraces deliberate product life shortening as part of its business strategy. Many other examples illustrate the general trend of shorter product lives in the electronics industry (e.g., Bakker et al. 2014).

The resulting impacts on the environment are manifold. For example, resource use in-creases with increasing number of manufactured durables. Also, increasing product disposal leads to creation of higher amounts of waste. At the same time, the impact from a purely economic perspective is unclear. Shorter product lives may influence both, the revenues as well as the costs of a company in positive as well as negative way.

Our paper questions the advantageousness of physical obsolescence practices form revenue perspective. In particular, we believe that product lives have become too short. To investigate this hypothesis, we develop an optimization model that explicitly accounts for durability as a determinant product attribute. Further, we conduct a consumer survey to estimate choice model parameters. As a case example, we focus our attention on the under-researched product category of electric toothbrushes. Initial results of our survey indicate strong importance of the durability attribute for consumers.

The contribution of the paper is threefold. First, the paper provides a prescriptive product (line) design model whose analysis provides insight into the potentially non-monotonic relationship between durability and profitability. Second, the paper derives design recommendations specifically for electric toothbrushes. Third, the paper bridges the fields of problem-centered prescriptive analytics and data-centered predictive analytics.

■ TB-14

Thursday, 10:40-12:00 - Wetterhorn

MCDA: Artificial Intelligence and Digitalization

Stream: Decision Analysis and Support
Invited session
Chair: *Florian Kaiser*

1 - Using Machine Learning to Include Planners' Preferences in Crew Scheduling Optimization

Theresa Gattermann-Itschert, Laura Maria Poreschack, Ulrich Thonemann

Optimization models have grown complex in many application areas due to including numerous soft goals by adding penalty terms to the objective function. Unlike hard constraints that ensure feasibility of solutions, these penalty terms push the solution in a desirable direction on top of a primary goal like cost optimization. In planning and scheduling, planners and human resources have preferences regarding the solution that are often intangible or a combination of interacting characteristics. Consequently, planners find it difficult to set penalty costs or to express their preferences in mathematical terms. Our approach is to learn these vague preferences with machine learning algorithms and to integrate them into a classic optimization model with the goal of creating schedules that are more favored. Considering a railway crew scheduling problem, we gather planner feedback on schedules created by an optimization algorithm. Planners rate whether they favor a certain duty by labeling it as good or bad. We train a random forest classifier to predict duty acceptance, giving the probability of a bad rating as output. We replace the complex construct of previous penalty terms by a single term penalizing the duties' probability of a bad rating. This generates schedules with similar costs, but higher planner acceptance by including more duties with preferred characteristics. Our findings show that the combination of machine learning and optimization models yields good results and increases solution acceptance. Our approach profits from machine learning to detect complex patterns regarding favorable duty characteristics and from optimization to create feasible and good solutions efficiently.

2 - A Lazy Expert: Predicting Lazy Constraints For Production Planning With Perishability Using Deep Learning
Lovis Heinrich, Hermann Graf von Westerholt, Sebastian Goderbauer, Marco Lübbecke

Modeling production as mixed integer linear programs (MILP) allows exploiting periods of low electricity price to save variable cost. Complicating aspects such as perishable materials significantly increase solving time of such optimization problems. This in turn often leads to untapped potential in solution quality, which is why more efficient solution processes are needed. For recurring production planning, the same MILP is solved repeatedly, with only the input data changing. Yet, experience about patterns in the solution process is usually not used. In this work, a production planning problem with perishable intermediates is considered. It is modeled using lazy constraints, i.e. complicating inequalities are separated and added on-the-fly during the solution process. It is then shown that a deep neural network can predict violated lazy constraints with high precision leveraging experience from previously solved instances. The new model outperforms the next fastest conventional model as well as the lazy method with up to 34% less solution time.

3 - Investor characteristics and their impact on the decision to use a robo-advisor
Stefan Wendt, Andreas Oehler, Matthias Horn

The purpose of our study is to analyze how retail investors' individual characteristics influence their decision to use a robo-advisor. Using a survey among 231 undergraduate business students, we analyze the influence of a broad range of individuals' characteristics on both the choice to use a robo-advisor and the amount the participants are willing to invest via the robo-advisor. In a univariate setup, we find that participants who are willing to use the robo-advisor are more willing to take financial risks, exhibit higher levels of extraversion, are more optimistic and less pessimistic than participants who are not willing to use the robo-advisor. Extraversion, optimism and pessimism do not remain significant in a logit regression analysis, but internal locus of control becomes significant with lower levels of internal locus of control increasing the likelihood to use the robo-advisor. Participants who are willing to use the robo-advisor would invest a larger amount in stocks and bonds than participants who are not willing to use the robo-advisor. We also find statistically significant differences between participants who exclusively use the robo-advisor for investments in stocks and bonds and participants who use the robo-advisor and additionally invest some money in stocks and bonds on their own.

4 - Process value oriented analysis of digitalization investments
Florian Kaiser, Marcus Wiens, Frank Schultmann

Digitalization of industrial processes is linked to improved efficiency, amplified productiveness, increased profitability and can enable new business models. Yet, this also constitutes a key challenge of quantifying the value of digitalization investments as information technology in itself does not generate value directly but indirectly by making value-related processes more efficient. Furthermore, digitalization of industrial processes also creates new vulnerabilities to economic systems and with these, new risks. Hence, it is of high strategic importance for companies to choose the right digitization strategy. Yet, the costs and benefits of digitization investments are associated with a high degree of uncertainty and managerial decisions are oftentimes observed to be non-optimal. These inefficiencies are at least partially based on a lack of methodological support for managerial decision making. We adress this problem by introducing a novel methodology that enables an ex-ante effort and benefit assessment from digitization projects. The starting point of this methodology is understanding the effects of digitalization investments on the dynamics of customer satisfaction and their effect on customer willingness to pay. The analysis is based on a process value analysis and petri net simulations. Furthermore, the methodology addresses uncertainties related to the investments using real options analysis. By using the developed methodology, decision makers are supported in assessing the feasibility of an investment as well as in determining a fair price for a digitization measure. In this way, investments in digitization, such as the acquisition of an industrial robot or the acquisition of software, can be analyzed

---

■ TB-15

Thursday, 10:40-12:00 - Silberhorn

GOR Young Researchers Awards

Stream: PC Stream
Invited session
Chair: *Alexander Martin*

1 - A two-phase stochastic programming approach to biomass supply planning for combined heat and power plants
Daniela Guericke

Due to the new carbon neutral policies, many district heating operators start operating their combined heat and power plants using different types of biomass instead of fossil fuel. The contracts with the biomass suppliers are negotiated months in advance and involve many uncertainties from the energy producer's side. The demand for biomass is uncertain at that time, and heat demand and electricity prices vary drastically during the planning period. Furthermore, the optimal operation of combined heat and power plants has to consider the existing synergies between the power and heating systems. We propose a solution method using stochastic optimization to support the biomass supply planning for combined heat and power plants. Our two-phase approach determines mid-term decisions about biomass supply contracts as well as short-term decisions regarding the optimal production of the producer to ensure profitability and feasibility. We present results based on ten realistic test cases placed in two municipalities.

2 - On the Rectangular Knapsack Problem: Approximation of a Specific Quadratic Knapsack Problem
Britta Schulze

In this work, we introduce the rectangular knapsack problem, which is a special case of the quadratic knapsack problem. It consists of a quadratic objective function, where the coefficient matrix is the product of two vectors, and a cardinality constraint, i. e., the number of selected items is bounded. In the literature, there are rather few results about the approximation of quadratic knapsack problems. However, the rectangular knapsack problem is a special variant for that we present an approximation algorithm that has a polynomial running time with respect to the number of items and guarantees an approximation ratio of 4.5. We show structural properties of this problem and prove upper and lower bounds on the optimal objective function value. These bounds are used to formulate the approximation algorithm. We also formulate an improved approximation algorithm and present computational results. The rectangular knapsack problem is, furthermore, the result of a quadratic scalarization of a bi-objective optimization problem. The scalarization can be used to find an efficient solution of the original problem that is optimal for the hypervolume indicator with respect to a given reference point. The hypervolume indicator is a quality measure for a representation based on the volume of the objective space that is covered by the representative points. We give a short outlook on possibilities and drawbacks of this scalarization.

3 - Airport capacity extension, fleet investment, and optimal aircraft scheduling in a multilevel market model: quantifying the costs of imperfect markets
Martin Weibelzahl

We present a market model of a liberalized aviation market with independent decision makers. The model consists of a hierarchical, trilevel optimization problem where perfectly competitive budget-constrained airports decide (in the first level) on optimal runway capacity extensions and airport charges by anticipating long-term fleet investment and medium-term aircraft scheduling decisions taken by a set of imperfectly competitive airlines (in the second level). Both airports and airlines anticipate the short-term outcome of a perfectly competitive ticket market (in the third level). We compare our trilevel model to an integrated single-level (benchmark) model in which investments, scheduling, and market-clearing decisions are simultaneously taken by a welfare-maximizing social planner. Using a simple six airports example from the literature, we illustrate the inefficiency of long-run investments in both runway capacity and aircraft fleet which may be observed in aviation markets with imperfectly competitive airlines.

4 - Optimal Line Planning in the Parametric City
Berenike Masing

Line Planning involves determining routes and assigning frequencies of service such that travel demands are met, while minimizing costs. The task can be modeled as a mixed integer linear program (MILP), whose objective includes a scalarization of user and operator costs, measured in travel and running times respectively. We study line planning in the "Parametric City", a generic, flexible city model developed by Fielbaum et al. for this purpose. The corresponding graph and demand are controlled by some parameter choices; the entire model is rotation symmetric. Fielbaum et al. work under the natural assumption that the line plans must also be symmetric. We reassess this assumption and find that there are cases in which optimal solutions can be asymmetric. Using group theory, we analyze the properties of symmetric solutions. Further, we derive a bound on the symmetry gap, which measures the deviation of a symmetric solution from the optimum. It is possible to construct instances, for which this gap becomes arbitrarily large. However, by fixing a single cost related factor in the Parametric City, we obtain an upper bound on the symmetry gap. The latter gives rise to an approximation algorithm. Supported by computational experiments, we conclude that in practice symmetric line plans provide good solutions for the line planning problem in the Parametric City.

■ TB-16

Thursday, 10:40-12:00 - Schilthorn

Technical Systems

Stream: OR in Engineering
Invited session
Chair: *Michael Stiglmayr*

1 - Optimization of wear related material costs of a hydrostatic transmission system via MINLP
Andreas Schmitt, Lena Charlotte Altherr, Philipp Leise, Marc Pfetsch

This contribution presents a method to find an optimal topology and control for a hydrostatic transmission system that is equipped with a hydraulic accumulator. The goal is to minimize wear in the system while fulfilling a predefined load cycle given by speed and force requirements during the retraction and extension of a piston. The design's degrees of freedom are the selection and the connection of optional switching valves and proportional valves with the system's piston, pressure source and tank. We derive a MINLP based on the graph representation of the system, where optional edges represent all reasonable connection possibilities of the components. The problem contains continuous variables for the quasi stationary flow, pressure conditions and valve conditions, as well as binary variables to include selection decisions and valve circuits. Nonconvex nonlinear functions model pressure conditions. While in previous work, we replaced all nonlinear relationships by piecewise linearizations and solved a MILP, in this work, we focus on solving the more accurate MINLP. Moreover, we extend the system model by integrating a hydraulic accumulator. To solve this new problem, we use a reformulation which no longer explicitly considers the variables for the valve lift. Furthermore, we approximate the valve wear by a quadratic polynomial depending on volume flow and pressure difference. To further speed up the solving process of the MINLP solver SCIP, we use a technique based on so-called perspective cuts, which we extend to the case of nonconvex functions. Our optimization results show that by adding a hydraulic accumulator to the system, one is able to reduce the wear related material costs by one third.

2 - Pumping system design with mixed integer programming: A computational study on formulation alternatives for variable network topology including discrete variables
Marvin Meck, Peter Pelz

Network optimization problems in engineering applications usually require both conservation of flow variables at network nodes and vanishing potential differences along a closed path, i.e., a circuit. Further, problems may involve variable network topology to model design and operation. Flow and potential differences are related by so-called constitutive equations; in some continuous network problems, the governing conservation laws can thus be reduced to a single equation, leading to non-linear optimization problems. For discrete topology optimization, this approach is impractical, as direct non-linear formulations consisting of integer and continuous variables are known to be challenging to solve. Instead, a common way to linearize those conditions is to use big-M constraints, which—in this particular instance—can be formulated in more than one way. In this paper we evaluate different formulation alternatives to model variable network topology involving discrete variables and taking into account both flow and potential variables. A computational study is presented for a practical problem. The problem considered involves optimization of pumping system designs with respect to optimal efficiency. Given a set of available equipment, the optimal selection, configuration and operation is found for given flow and head requirements. Variations of this problem have been subject of research in multiple contributions before and the problem was shown to be computationally demanding, highlighting the need for efficient problem formulations. Due to the similarities to other engineering network problems, the results are expected to be of relevance for other problems outside our example.

3 - A Finite Element Approach for Trajectory Optimization in Wire-Arc Additive Manufacturing
Johannes Schmidt, Johannes Buhl, Armin Fügenschuh

In the additive manufacturing process of wire-arc additive manufacturing (WAAM), a moving heat source melts an electrode wire to deposit it through an electrical arc. The desired workpiece is built layer-wise on an underlying substrate plate. If it has a complex geometry, it is divided up into subparts with simpler shapes and built subpart-by-subpart. If necessary, the heat source can move without welding, called deadheading. The enormous heat of the welding head is transferred within the workpiece through conduction and radiation, leading to large temperature gradients. These temperature differences cause strain, deformation of the workpiece, or even thermal cracks. Thus a homogenous temperature distribution is desirable by minimizing these gradients. Considering a single layer of the workpiece as a graph, we describe the optimization problem of finding a eulerian path with a most homogenous temperature distribution. If the graph is non-eulerian, the necessary deadheading moves lead to additional edges. The heat equation describes the conduction, and there are additional constraints for the heating process and radiation to track the temperature distribution within the workpiece while minimizing the heat gradients between neighboring nodes of the graph. We formulate this problem as a mixed-integer linear programming model. To this end, we discretize the heat equation and linearize the radiation term. Then we demonstrate its solvability using standard mixed-integer solvers for several test instances. Furthermore, we carry out numerical experiments about the approximation of thermal radiation and compare the computed results to real processed workpieces.

4 - Hypervolume Scalarization for Biobjective Shape Optimization
Michael Stiglmayr, Johanna Schultes, Kathrin Klamroth

We consider a biobjective shape optimization problem maximizing the mechanical stability of a ceramic component under tensile load while minimizing its volume. Stability is thereby modeled using a Weibull-type formulation of the probability of failure under external loads. The PDE formulation of the mechanical state equation is discretized by a finite element method on a regular grid. To solve the discretized biobjective shape optimization problem we suggest a hypervolume scalarization, with which also unsupported efficient solutions can be determined without adding constraints to the problem formulation.

Furthermore, maximizing the dominated hypervolume supports the decision maker in identifying compromise solutions. We investigate the relation of the hypervolume scalarization to the weighted sum scalarization and to direct multiobjective descent methods. Since gradient information can be efficiently obtained by solving the adjoint equation, the scalarized problem can be solved by a gradient ascent algorithm.

Thursday, 13:00-14:00

■ TC-01

Thursday, 13:00-14:00 - Bundeshaus

SP talk Archetti

Stream: PC Stream
Sponsored session
Chair: *Claudia Archetti*

1 - Formulations and exact solution approaches for the Inventory Routing Problem
Claudia Archetti

In the last decades, Inventory Routing Problems (IRPs) have been attracting growing attention from the research community, due to the real-world applications, in integrated logistics and supply chain management, and the intellectual challenges that their study poses. The interest in studying IRPs is mainly motivated by the potential benefits coming from combining inventory management and routing decisions. Solving two separate optimization problems for inventory management and routing typically produces sub-optimal solutions to the integrated problem. Tackling directly the integrated problem causes an increase of the computational burden, but tends to provide considerably better solutions. In the IRP the goal is to determine an optimal distribution plan to replenish a set of customers by routing a limited fleet of capacitated vehicles over a discrete planning horizon. Each customer consumes a per period quantity of product and has a maximum inventory capacity. The objective is to minimize the total distribution cost, that includes the routing and the inventory holding costs. Different formulations have been proposed in the literature for modelling the problem, giving raise to various exact solution approaches, based on branch-and-price and branch-and-cut. The goal of this talk is to analyse the formulations and study their pros and cons. We will mainly focus on compact formulations, focusing on properties and links between formulations with vehicle indices and aggregated formulations.

■ TC-02

Thursday, 13:00-14:00 - Zytglogge

SP talk Kuhn

Stream: PC Stream
Sponsored session
Chair: *Daniel Kuhn*

1 - A Unifying Framework for Robust and Distributionally Robust Optimization
Daniel Kuhn

Robust and distributionally robust optimization are modeling paradigms for decision-making under uncertainty where the uncertain parameters are only known to reside in an uncertainty set or are governed by any probability distribution from within an ambiguity set, respectively, and a decision is sought that minimizes a cost function under the most adverse outcome of the uncertainty. In this talk, we develop a general theory of robust and distributionally robust nonlinear optimization using the language of convex analysis. Our framework is based on a generalized 'primal-worst-equals-dual-best' principle that establishes strong duality between a semi-infinite primal worst and a non-convex dual best formulation, both of which admit finite convex reformulations. This principle offers an alternative formulation for robust optimization problems that may be computationally advantageous, and it obviates the need to mobilize the machinery of abstract infinite-dimensional duality theory to prove strong duality in distributionally robust optimization. We illustrate the modeling power of our approach through convex reformulations for distributionally robust optimization problems whose ambiguity sets are defined through general optimal transport distances, which generalize earlier results for Wasserstein ambiguity sets.

■ TC-03

Thursday, 13:00-14:00 - Münster

SP talk Parragh

Stream: PC Stream
Sponsored session
Chair: *Sophie Parragh*

1 - Branch-and-bound for multi-objective (mixed) integer linear programming: key ingredients, challenges, and motivating applications
Sophie Parragh

As promoted by the European Green Deal, policy makers and companies increasingly strive for minimizing environmental impact, in addition to other objectives such as keeping costs low or ensuring a high customer service level. Unfortunately, the minimum cost solution is rarely the best from an environmental perspective or from the perspective of customer service. Optimizing conflicting objectives concurrently results in a set of optimal trade-off or efficient solutions which have the property that neither objective can be improved without deteriorating at least one other objective. The image of these solutions in objective space is called the non-dominated frontier or Pareto front. The wide range of practical problems which can be modeled as mixed integer linear programs (MILPs), and involve more than one objective, motivates the development of generic exact methods as general purpose tools to solve them. In this talk, we first give a brief overview of recent advances in exact methods for solving bi- and multi-objective MILPs which compute at least one solution for each point on the Pareto front. They are commonly classified as either criterion space search methods, which work in the space defined by the objective functions, or as decision space search methods, which have been mainly generalizations of branch-and-bound algorithms. We then focus on the most recent successful branch-and-bound schemes, which do not exclusively work in the decision space. We discuss their key ingredients, such as bound set generation, branching rules, and primal heuristics. Finally, we highlight motivating applications in logistics, discuss open challenges and indicate promising directions for future research.

Thursday, 14:20-15:40

■ TD-04

Thursday, 14:20-15:40 - Eiger

Software for OR - Modeling II

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Frederik Proske*

1 - AIMMS model development tools
Arthur d'Herbemont

We will demonstrate the possibilities of AIMMS for analyzing your challenging models. What if you hit an infeasibility, or your model is poorly scaled and provide instable solutions? Developer tools are available for analysis and resolving these issues (such as the Math Program Inspector and Auto-Scaling tool).

We will also share about model development collaboration. All the work presented will be open sourced.

2 - Model deployment in GAMS
Frederik Proske, Robin Schuchmann

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, interest in alternative deployment methods is also growing in the field of mathematical optimization. In this talk we present a new interface to deploy GAMS models. We show how to turn a 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.

3 - Operationalizing analytic models in a business user friendly environment
Sergio Morales Enciso

You have a cutting-edge mathematical model. Now, how are you planning to deploy it? For an operational environment you might require deploying your model as a service (machines talking to machines), while for a strategic problem you might need to create a GUI for the subject matter expert to configure several equally optimal scenarios (efficient frontier) to present to the stakeholders who will select one based on the business needs. In any case, there are additional requirements to consider. Will you need to execute concurrent models? How will data be managed to achieve an efficient what-if scenario management for side-by-side comparison? Is there any review and approval workflow to be enforced before deploying a model into production? What about security and user management? Do you need LDAP integration and https support? Unless you have an army of developers at your disposal -and plenty of time-, you will probably be better-off using an enterprise grade platform that offers all the above functionalities and more off-the-shelf so that you can focus on delivering value to your organization. In this talk I will show how easy Xpress Insight makes it to bring your analytic models into production.

4 - 40 Years of OR Software Development: Lessons Learned
John Chinneck

A summary of advice and hard lessons learned during 40 years of developing algorithmic software for operations research. Things to consider when embarking on a new project: programming and modelling languages, basic numerical methods, solvers, software libraries, test sets, experiment design, etc.

■ TD-05

Thursday, 14:20-15:40 - Mönch

Software for OR - NLP

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Renke Kuhlmann*

1 - TOPAS Model Fitting: Improving the Modeling Process of Dynamical Systems using Parametric Sensitivities from Nonlinear Optimization
Marek Wiesner, Arne Berger, Wiebke Bergmann, Kai Schäfer, Carla Dittert, Petr Shulpyakov, Christof Büskens

Accurate models are crucial for the successful simulation, optimization, and control of real-world processes. Often, such processes are modeled with ordinary differential equations which depend on several parameters. In most realistic scenarios, these parameters must be fitted to the given process using measurements. This task is commonly referred to as parameter identification. How the result of such a parameter identification relates to the measurements can be complex. In many scenarios, it is not obvious how the measurements affect the identified parameters.

TOPAS Model Fitting guides the user through the parameter identification and supports in data selection, choice of the algorithmic approach, and visualization of the results. A notable feature is the analysis of the dependence of the identified parameters on specific measurement regions. It helps to validate the chosen modeling approach or hints towards inaccuracies within parts of the model structure. This can lead to a faster modeling process.

The previously mentioned feature is implemented using parametric sensitivity analysis from nonlinear optimization. First, the measurements are parameterized by a B-spline regression. The optimal B-spline coefficients are then considered as perturbations in the parameter identification problem. Based on the parametric sensitivities of the identified parameters with respect to the B-spline coefficients, the importance of specific measurement regions for individual parameters is determined.

In this talk, TOPAS Model Fitting will be used for the identification of a real-world problem from autonomous systems. The focus will be on the analysis of the relationship between the identified parameters and the measurements and how this improves the modeling process.

2 - Graph-Structured Nonlinear Programming: Properties, Algorithms, and Software
Victor Zavala, Jordan Jalving, Sungho Shin

In this talk we review recent advances in the formulation and solution of graph-structured nonlinear programs (NLP). This is a broad problem class in which the algebraic structure of the NLP can be expressed as a graph; typical application examples include dynamic optimization (graph is a line), stochastic optimization (graph is a tree), network optimization (graph is network topology), and PDE optimization (graph is a mesh) but the abstraction allows us to target applications that embed complex graphs (e.g., stochastic PDE optimization and time-dependent network optimization). We provide a brief overview of theoretical properties of graph-structured NLPs and show how these enable the design of new types of decomosition algorithms. Specifically, we show that these problems possess a property that we call "Exponential Decay of Sensivity" and show that this enables the design of a new and powerful decomposition paradigm that we call "Overlapping Schwarz Decomposition." We present a Julia-based modeling package (Plasmo.jl) that leverages the graph structure and show how this facilitates model construction, visualization, and process (e.g., partitioning and aggregation). We also present a Julia-based solver package (MadNLP.jl) and demonstrate that this can accelerate the solution of large-scale problems arising in energy infrastructures.

3 - Computationally Efficient Parallel Nonlinear Programming in PyNumero and Parapint
Carl Laird

PyNumero is a package that supports rapid development of computationally efficient, serial and parallel nonlinear optimization algorithms in Python. While numerical algorithms are often written in compiled programming languages (e.g., FORTRAN, C, C++) for performance, these low-level languages significantly increase implementation time. PyNumero aims to provide a high-level programming environment for algorithm development without sacrificing computational performance. Built upon Pyomo, PyNumero is compatible with Numpy and Scipy, and provides support for common, high-performance linear solvers typically used in NLP algorithm development. A key feature of PyNumero is support for parallel and serial block-structured matrices that allow straightforward composition of linear systems used in NLP algorithms and decomposition-based approaches. In this presentation, we will provide background information on the design and use of PyNumero and illustrate computational performance of the package. We will also introduce ParaPint, a package built on top of PyNumero that provides a suite of parallel NLP solvers for structured problems. ParaPint has demonstrated scalability to over 1000 cores with near perfect parallel efficiency. We will present the underlying decomposition algorithms and several parallel case studies.

4 - Second-Derivative Methods SQP for Large-Scale Non-Convex Nonlinear Optimization
Elizabeth Wong, Philip E. Gill, Alexander Guldemond

A sequential quadratic programming (SQP) method is discussed that uses both first and second derivatives of the problem functions. The method is based on using a shifted primal-dual interior method to solve the quadratic programming (QP) subproblem.

The use of a shifted primal-dual interior method provides two important benefits. First, the interior method can be adapted to exploit a good estimate of the solution of the QP subproblem (i.e., it can be "warm-started"). Second, it implicitly regularizes the subproblem and allows convergence under weak assumptions on the problem. The discussion will also focus on the treatment of infeasible and unbounded subproblems. Some numerical results on large nonconvex problems will be presented.

■ TD-06
Thursday, 14:20-15:40 - Jungfrau

Bi-Level Optimization

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Markus Sinnl*

1 - An Exact Projection-Based Algorithm for Bilevel Mixed-Integer Problems with Nonlinearities
Maximilian Merkert, Galina Orlinskaya, Dieter Weninger

Solving bilevel mixed-integer problems with lower-level integer variables is extremely challenging as a single-level reformulation that is suitable for MINLP solvers is usually not available. In order to solve such problems, we enhance an approximative projection-based algorithm for mixed-integer linear bilevel optimization problems from the literature to become exact under one additional assumption. This assumption still allows for discrete and continuous variables on both levels, but forbids continuous leader variables to appear in lower-level constraints and thus ensures that a bilevel optimum is attained. In addition, we extend our algorithm to make it applicable to a wider problem class. This setting allows nonlinear constraints and objective functions on both levels under certain assumptions, but still requires that the lower-level problem is convex in its continuous variables. We also discuss computational experiments on modified library instances.

2 - Presolving Linear Bilevel Optimization Problems
Dieter Weninger, Thomas Kleinert, Julian Manns, Martin Schmidt

Linear bilevel optimization problems are known to be strongly NP-hard and the computational techniques to solve these problems are often motivated by techniques from single-level mixed-integer optimization. Thus, during the last years and decades many branch-and-bound methods, cutting planes, or heuristics have been proposed. On the other hand, there is almost no literature on presolving linear bilevel problems although presolve is a very important ingredient in state-of-the-art mixed-integer optimization solvers. We carry over standard presolve techniques from single-level optimization to bilevel problems and show that this needs to be done with great caution since a naive application of well-known techniques does often not lead to correctly presolved bilevel models. Our numerical study shows that presolve can also be very beneficial for bilevel problems but also highlights that these methods have a more heterogeneous effect on the solution process compared to what is known from single-level optimization.

3 - A branch-and-cut algorithm for submodular interdiction games
Kübra Tanınmış, Markus Sinnl

Many relevant applications from diverse areas such as marketing, wildlife conservation, or defending critical infrastructure can be modeled as interdiction games. In this work, we introduce interdiction games whose objective is a monotone and submodular set function. Given a ground set of items, the leader interdicts the usage of some of the follower's items to minimize the objective value achievable by the follower, who seeks to maximize a submodular set function over the uninterdicted items subject to knapsack constraints.

We propose an exact branch-and-cut algorithm for this kind of interdiction games. The algorithm is based on interdiction cuts that capture the follower's objective function value for a given interdiction decision of the leader and exploit the submodularity of the objective function. We also present extensions and liftings of these cuts and discuss additional preprocessing procedures.

We test our solution framework on the weighted maximal covering interdiction game and the bipartite inference interdiction game. For both applications, the improved variants of our interdiction cut perform significantly better than its basic version. For the weighted maximal covering interdiction game for which a mixed-integer bilevel linear programming (MIBLP) formulation is available, we compare the results with those of a state-of-the-art MIBLP solver. While the MIBLP solver yields a minimum of 54% optimality gap within one hour, our best branch-and-cut setting solves all but 4 of 108 instances to optimality with a maximum of 3% gap among unsolved ones.

4 - On solving fortification games via branch-and-cut
Markus Sinnl, Markus Leitner, Ivana Ljubic, Michele Monaci, Kübra Tanınmış

Fortification games, also known as sequential defender-attacker-defender problems, are a class of trilevel optimization problems with many applications in areas such as military operations, facility and power grid protection or survivable network design. These problems are an extension of interdiction problems, i.e., attacker-defender problems, with an outer level which allows for defense against the attacker: In the outer level, the defender can select some assets to protect, in the middle level, the attacker can select some of the unprotected assets to attack, and in the inner level, the defender solves an optimization problem over the non-attacked assets.

In this talk, we present an single-level mixed-integer programming reformulation for fortification games by introducing fortification cuts, which allow modeling the objective function of the fortification games in an outer-approximation-fashion. Based on these cuts, we develop an exact branch-and-cut algorithm for fortification games. We discuss lifting procedures for fortification cuts, as well as separation and implementation details. We also present a computational study on instances from literature, including a comparison to a state-of-the-art algorithm for fortification games.

■ TD-07
Thursday, 14:20-15:40 - Niesen

Metaheuristics and Feature Selection

Stream: Heuristics, Metaheuristics and Matheuristics
Invited session
Chair: *Pongchanun Luangpaiboon*
Chair: *Pasura Aungkulanon*

1 - Experimental evaluation of the predictive quality induced by some features selection algorithms

Thibault Agondja, François Delbot, Jean-François Pradat-peyre

One goal of machine learning is to obtain a model with the best predictive quality. To do this, data scientists select the available features and test the different learning methods on their data. Finally, they keep the best model. This empirical exploration can be explained by the fact that the performance of a model vary depending on the data (quality, quantity, number, type of features, etc.).

In previous works, we have compared heuristics to perform features selection. Our evaluation criterion was the predictive quality obtained by using the same machine learning method. We also conducted an experiment to determine if the performance of these heuristics could vary depending on the learning method used.

However, this work did not allow us to evaluate the absolute performance, i.e. the value of the ratio between the predictive quality obtained and the best predictive quality that could be obtained with an optimal features selection.

In this work we perform an experimental study on a dataset containing few features (issued from the medical domain), which allows us to enumerate all the subsets of features and thus to determine the one that allows to optimize a learning method. Then, we use 10 heuristics to perform a features selection that we use for machine learning with 5 different methods. We are thus able to evaluate the true performances of the different learning methods as well as the impact of the features selection on their predictive quality.

2 - Continuous Optimization Problems via a Novel Metaheuristic: The Clean Room Learning Algorithm

Pasura Aungkulanon, Roberto Montemanni, Pongchanun Luangpaiboon

This research proposes a newly developed metaheuristic algorithm for continuous optimization named the CleanRoom Learning algorithm (CRL), inspired by the design behavior of airborne particles controlled, and constructed and used in a manner to reduce the introduction, generation, and retention of particles inside a cleanroom. Cleanrooms are a specially constructed enclosed space with environmental control of particulates, temperatures, humidity, electrostatic discharge (ESD), air pressure, airflow patterns, air motion, vibration, noise, viable organisms and lighting. CRL is a swarm intelligence search algorithm especially designed for continuous problems that mimics the operations required to keep the characteristics of a cleanroom. There are four fundamental principles behind the CRL algorithm. First, candidates with deteriorated objective function values or contaminants are kept out of the controlled environment. Second, the evolutionary mechanisms cannot worsen candidate solutions. Third, candidates with bad objective function values or contaminants cannot accumulate in the. Fourth, existing candidates with undesired objective function values or contaminants must be eliminated as rapidly as possible. Experimental results on standard problems from the literature are presented to validate the new algorithm through a comparison with other metaheuristic methods previously appeared.

3 - Sheepdog Algorithm: A new bio-inspired approach for feature selection.

Shubbham Gupta, Paula Carroll, Michael Fop

A feature is a measurable property of interest of the data. In recent years, due to the increased accessibility of data sources, the number of features available in machine learning applications has grown exponentially, demanding the development of scalable methods for selecting those features most useful for a task. For supervised classification tasks, feature selection methods select a subset of features that best discriminate the target classes, leading to dimensionality reduction and improved classification performance. Many approaches have been proposed in the literature, including statistical and metaheuristics approaches. Among the latter, there are bio-inspired algorithms. These metaheuristic algorithms are inspired by different biological phenomena and obtain an optimal solution in a reasonable computational time due to their ability to navigate through nonlinear and complex solution space.

In our work, the SheepDog Algorithm (SDA) is proposed as a wrapper method for feature selection. It mimics a sheepdog's behaviour and controls the herding of a flock of sheeps on farms. It is an example of one individual causing many unwilling individuals to move in the same direction. Every sheep denotes a subset of features, and they are moved in an encoded map defined by the count of features in the subset and the accuracy of the classification model based on the selected features. The algorithm's task is to move the flock towards a region of low feature count and high accuracy. The feature selection algorithm is developed using this idea, and its performance is compared with other existing algorithms for feature selection. The proposed method is tested on simulated data experiments and illustrative benchmark datasets, showing good results.

4 - The node edge and arc routing problem with stochastic customers and service times

Oscar Téllez, Véronique François, Yasemin Arda

This presentation addresses a node, edge, and arc vehicle routing problem with stochastic customers and service times. A maximum duration is defined for each route, where the duration of each route is a random variable in this stochastic environment. We thus model the maximum duration constraint of each route as a chance constraint. In the defined methodology, the solutions obtained with the probabilistic knowledge at hand cover all customers with non-zero occurrence probability. After the demands are realized, only a subset of customers will actually be served. As a recourse strategy, a customer that does not require to be served is skipped in its corresponding route, while keeping the rest of the visiting sequence unchanged. This research is motivated by a real application in the context of postal delivery services. Those services are provided by couriers who perform daily rounds in fixed geographic areas, called districts, typically defined for a long period of time based on the expected demand. However, daily demand variations can negatively impact the couriers' workload, creating extra working hours. We address here the problem of designing routes so that the workload of couriers respects the imposed maximum working duration for most demand realizations.

■ TD-08

Thursday, 14:20-15:40 - Stockhorn

Storage and flexibility markets

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

1 - Quantifying Value Pools for Distributed Flexible Energy Assets: A Mixed Integer Linear Programming Approach

Reinhard Madlener, Jan Martin Specht

The sectoral coupling of heat, mobility, and electricity as well as the diffusion of distributed energy resources (DER) for electricity generation and storage have the potential to significantly impact the electric grid. On the one hand, an uncontrolled operation of these DER will potentially result in a substantial need for grid enhancement and substantial costs for society. On the other hand, DER bear substantial potential for flexibility that could, if utilized properly, enhance grid stability, and thus be beneficial to system operators and customers alike. In this paper, we introduce a combination of a heuristic with a linear optimization model for the electricity demand of a single-family household with the option to include an electric vehicle. The model allows for the separate and simultaneous, economic optimization of up to five use cases: (1) maximization of self-consumption; (2) avoidance of load peaks; (3) utilization of flexible electricity prices; (4) provision of frequency control reserve (FCR); and (5) reduction of battery aging. We investigate costs and benefits for each use case and, based on data and legislation for Germany, find several of the use cases to result in cost savings of up to EUR 50 per year. Surprisingly, simultaneous investigation of multiple use cases reveals that some combinations show synergetic rather than the expected cannibalizing effects. The insights gained seem to be of special importance in the context of designing business models aimed at tapping unused flexibility potentials of distributed energy resources.

2 - Prosumer Empowerment through Community-Power-Purchase-Agreements: A Market Design for Peer-to-Peer Swarm Grids

Jens Weibezahn, Raluca Dumitrescu, Alexandra Lüth, Sebastian Groh

Bangladesh is the largest solar home systems (SHS) market in the world, with more than 4.13 million SHS installed between 2003 and 2019, through a soft financing program run by the Government's Infrastructure Development Company Limited. The deep rural penetration of SHS and the average 30% of surplus electricity per SHS are just two of the factors that have enabled the installation of the world's first rural area Peer-to-Peer (P2P) microgrids or P2P swarm grids. However, the trading of electricity between peers heavily relies on motivational drivers, as the design of the features and rules on how to buy or sell electricity locally are both un-regulated and in their early stages. One feature of the P2P swarm grid is the interconnection with the national grid infrastructure, through which not only electricity can be shared, but also other benefits. There are several market design approaches proposed for P2P grids, however their foci are on established electricity markets in the Global North. In this paper we establish a market design methodology for P2P swarm grids in the Global South, in which the peers are rural households and small businesses, with installed capacities of up to 250 Wp. We introduce the community power purchase agreement (CPPA) - the tariff received by the P2P swarm grid for servicing the grid, once it is interconnected with the national grid. We conduct the market design modelling for a P2P swarm grid in Dhobaura, Mymensingh, Bangladesh using a determination scheme for the CPPA tariff and a market simulation based on a Mixed Complementarity Problem. Finally, we provide policy recommendations for the public sector to adopt CPPA versus net-metering coupled with viability gap financing.

3 - Design of flexible short-term energy contracts - An analysis of trading strategies on the continuous intraday market

Michael Naumann

Short-term fluctuations in electricity prices allow cost-optimized production scheduling by shifting energy-intensive processes to periods of favorable electricity prices, for which the day-ahead prices of EPEX Spot provide a reference point. However, the producing companies are usually not involved in trading at the power exchange themselves; furthermore, the day-ahead prices represent the result of a finished auction and are therefore neither plannable nor tradable after the end of the auction.

We propose the offering of short-term variable energy contracts for a brief period after the end of the day-ahead auction. Such contracts involve the flexible delivery of power on the following day at the market price of the day-ahead auction plus a premium for the offering energy trader. They would allow traders to pass on the day-ahead prices to the end customer and thus make them a predictable variable. The trader, now exposed to price risk, can buy the required amount of electric power at the continuous intraday market.

We analyze the price differences on this market in relation to the contract price and thus the day-ahead price. We develop several trading strategies and test them empirically using the order books of EPEX Spot for different trading volumes. The strategies rely on the day-ahead price and the bid-ask spread. Adjusted renewable forecast data and the weighted average intraday market price are meaningless due to high volatility and the need for trader coverage. We show that, on average, a relatively small premium to the day-ahead price is sufficient for the trader to break even, with a slight increase in the premium for larger volumes. Finally, we identify renewable energy forecast errors in particular as drivers of the premiums.

■ TD-09

Thursday, 14:20-15:40 - Gantrisch

Microgrids and district heating

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

1 - Calculating the cost optimal integration of renewable electricity in a district heating system

Markus Schindler, Lukas Gnam, Christian Pfeiffer, Markus Puchegger, Patricia Jasek

The major disadvantage of renewable energy sources (RES) such as photovoltaic systems or wind turbines is their highly fluctuating production output. The resulting production peaks can lead to instabilities in the energy grid. In Austria, it is currently the case that energy produced by RES is fed in with a fixed subsidized feed-in tariff. The "Erneuerbaren Ausbau Gesetz" that will soon come into force on the other hand, provides for tendering and market premium models for renewable electricity in the future. Therefore, it is also necessary to develop additional distribution channels for green electricity. On the other hand, it is also essential for the energy transition to adapt the district heating (DH) networks in such a way that CO2 emissions in heat production are reduced and economic advantages for the DH grids are achieved. In order to mitigate the two negative effects presented above, a sector coupling (SC) of the power grid with the DH grid presents itself as an efficient solution. Hence, this study investigates different approaches on how to utilize heat pumps (HPs) or electric boilers for a successful and efficient SC. The evaluation is based on a mixed integer linear programming model of two real-world DH networks. Both networks are powered by a biomass plant (BMP) and are extended using a wind farm powered HP or boiler. To achieve the optimum energy yield when a HP is operated, there are two different operating modes: in summer, the HP obtains the energy from the air; in winter, the energy is obtained from the BMP by means of flue gas condensation. In this work, the amount of renewable energy that can be fed into the DH networks over one year is calculated based on the models created and compared to an optimization based on rolling data series.

2 - A Conceptual Framework to Determine the Economically Optimal Level of Microgrid Resilience

Sammit Vartak, Reinhard Madlener

The increased frequency in recent years of electrical outages due to natural disasters has necessitated the enhancement of the resilience of the power grids. Microgrids are considered as one of the effective measures for the resilience enhancement due to their ability to island themselves during an outage and ensure continuity of supply. While planning a microgrid for resilience enhancement, it is important to evaluate the level of resilience possessed by the microgrid itself. Currently, there is no standard framework for resilience evaluation of microgrid. The available resilience evaluation frameworks in the literature overlook the economic parameters which are important in the decision making about the investment in resilience enhancement. To bridge this gap, a new methodology is proposed for evaluating the economically optimal level of microgrid resilience. Availability based resilience evaluation framework is used for quantification of the resilience. That is, the resiliency of a microgrid is quantified using the microgrid's availability during the islanded mode. The quantified resilience values are monetized using the economic indicator Value of Lost Load. The economically optimal resilience level for different combinations of loads is evaluated using the Net Present Value method.

3 - A generic stochastic network-flow formulation forproduction optimization of district heating systems

Daniela Guericke, Amos Schledorn, Henrik Madsen

District heating is an important component in the EU strategy to reach the set emission goals, since it allows an efficient supply of heat while using the advantages of sector coupling between different energy carriers such as power, heat, gas and biomass. Most district heating systems use several different types of units to produce heat for hundreds or thousands of households. 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 use the synergy effects of excess heat from electricity production. We propose a generic network-flow based mathematical formulation for the operational production optimization in district heating systems. The generality of the model allows it to be used for most district heating systems although they might use different combinations of technologies in different system layouts. The mathematical formulation is based on stochastic programming to account for the uncertainty of production from non-dispatchable units such as solar thermal units. Furthermore, the model can serve as a basis for deciding on the electricity market participation of CHP units through the determination of bids to the markets. We present results from real cases in Denmark with different requirements.

4 - A reinforcement learning approach to home energy management for modulating heat pumps and photovoltaic systems

Lissy Langer, Thomas Volling

Efficient sector coupling in the residential building sector plays a key role in supporting the energy transition. In this study, we analyze the potential of a self-learning adaptive system to control a home energy management system. We conduct this study by modeling a representative building with a modulating air-sourced heat pump, a photovoltaic system, a battery, and thermal storage systems for floor heating and hot-water supply. In addition, we allow grid feed-in by assuming a fixed feed-in tariff and consider user comfort. In our numerical analysis, we benchmark our reinforcement learning results, derived by implementing the DDPG algorithm, with the optimal solution generated with model predictive control using a mixed-integer linear model assumming full information. We compare costs, self-sufficiency, as well as system behavior for representative summer and winter months. At the same time, we evaluate the potential for adaptive control in a stochastic, highly dynamic setting. Our input data and models, written in the Julia programming language using mainly the JuMP, Flux, and Reinforce package, are available in an open-source manner.

■ TD-10

Thursday, 14:20-15:40 - Schreckhorn

Rail, air, bus, and underground transportation

Stream: Logistics and Freight Transportation
Invited session
Chair: *Ricardo Euler*

1 - Multi-start Heuristics for Unit-Capacity Orienteering Problems

Alexander Beckmann, Jürgen Zimmermann

We address a planning problem for the underground transit of goods in mining companies. Transport containers are used for intermodal transport at the surface, through the shaft, and in drifts underground. Different types of transport containers allow the transport of bulk freights, liquids, and unit loads. Furthermore, machines can be made mobile by installing them on the containers' platform. A problem instance contains tasks and capacities for their fulfillment. Tasks are transports of containers from their current locations to given destinations and deliveries and pickups of empty containers and materials. Besides, we address combinations of those tasks with preceding constraints, such as transports of material, requiring the delivery of an empty container, or the pickup of an unloaded container. Storage locations provide a stock of empty containers and materials and are destinations for pickup containers and materials. Heterogenous workers and a fleet of heterogenous vehicles are available for performing the tasks. Each task has an assigned profit and can have a due date, which grants additional profit on observance. The objective function is to maximize the benefit of fulfilled tasks and met due dates. We developed two heuristic solution approaches, creating tours either consecutively or in parallel. Furthermore, these constructive algorithms are extended to multi-start versions using randomization of vehicle and worker selections, container-type selection, and insertion criteria.

2 - Decision Support System for Rail Depot Planning

Gian Tuor, Fabian Leuthold, Bruno Pfeiffer, Harold Tiemessen

A critical part of the planning process of any railway passenger operator is the operational depot planning. This task is extremely dependent on the preceding planning processes, such as rolling stock planning and timetabling, and is highly sensitive to changes. Therefore, it is carried out as late as possible, which leads to high time pressure. Moreover, efficient depot planning will become even more crucial in the future due to an emerging increase in passenger rail traffic and the associated increase in rolling stock. The operational depot planning problem can be divided into five subproblems: matching of arriving and departing train units, parking, routing, cleaning, and crew planning. In this research, we focus on the parking problem, often denoted as the Track Assignment Problem (TAP). The topology of the shunt yard and the arrival and departure times of all train units are inputs to the TAP. Objective is to assign train units to tracks, such that the depot plan is feasible and minimizes some user-defined cost-function. For a track assignment to be feasible, departing train units may not be blocked by parked train units and the capacity of each shunt track might not be exceeded (among other constraints). In existing literature, TAP are often formulated as a Set Partitioning Problem and solved using column generation to overcome the problem of the exponential number of decision variables. We have developed an MIP formulation with a quadratic number of decision variables and a simple but effective construction heuristic that can be combined with local search. We have used Google OR Tools to solve the MIP models. We show the performance of the MIP model and the heuristic based on real-life test cases from two European railway companies.

3 - Large Neighborhood Search for a Multi-Objective Dial-a-Ride Problem in Shared Micro-Transit Services

Christian Truden, Mario Ruthmair, Kerstin Maier

We investigate sustainable and reliable forms of shared micro-transit services to reduce carbon dioxide emissions caused by individual transport. The service involving a fleet of small buses is designed as a feeder system to existing public transport lines and is primarily intended for commuters that need to travel regularly from remote rural areas to urban centers and back. The underlying optimization problem is a variant of the dial-a-ride problem with three objectives: (i) maximizing the number of accepted customer transportation requests, (ii) minimizing the total distance driven (which is related to reducing CO2 emissions), and (iii) minimizing the total excess ride time of passengers (compared to shortest ride times). These conflicting objectives represent the targets of service providers (i+ii), governments (ii), and customers (i+iii). We propose a large neighborhood search similar to the one in Ropke and Pisinger (2006), but adapted to work with multiple objectives. To this end we maintain and steadily update a pool of non-dominated solutions, and consistently evaluate removals, insertions, and acceptance with respect to all three objectives. A case study is performed for a rural region in Austria, based on existing micro-transit and public transport stations and reasonably generated transportation requests.

4 - ULD Build-Up Scheduling with Dynamic Batching in an Air Freight Hub

Ricardo Euler, Ralf Borndörfer, Timo Strunk, Tuomo Takkula

Air freight is usually shipped in standardized unit load devices (ULDs). The planning process for the consolidation of transit cargo from inbound flights or locally emerging shipments into ULDs for outbound flights is called build-up scheduling. More specifically, outbound ULDs must be assigned a time and a workstation subject to both workstation capacity constraints and the availability of shipments which in turn depends on break-down decisions for incoming ULDs. ULDs scheduled for the same outbound flight should be built up in temporal and spatial proximity. This serves both to minimize overhead in transportation times and to allow workers to move freight between ULDs. We propose to address this requirement by processing ULDs for the same outbound flight in batches.

For the above build-up scheduling problem, we introduce a multi-commodity network design model. Outbound flights are modeled as commodities; transit cargo is represented by cargo flow volume and unpack and batch decisions are represented as design variables. The model is solved with standard MIP solvers on a set of benchmark data. For instances with a limited number of resource conflicts, near-optimal solutions are found in under two hours for a whole week of operations.

■ TD-11

Thursday, 14:20-15:40 - Wildstrubel

Scheduling and Visualization in Supply Chain and Production Management

Stream: Supply Chain and Production Management
Invited session
Chair: *Sebastian Scholz*

1 - Optimization of production scheduling under demand-side management

Hermann Graf von Westerholt

The energy sector in Germany (and other industrial nations) is in a state of transition: electricity generation is moving from fossil-fuel based power plants to renewable sources of energy, such as wind and solar power. Supply from these energy sources is known to be volatile which poses challenges to transmission system operators.

One approach to account for fluctuations in electricity supply lies in taking measures that readjust electricity consumption accordingly. This is known as demand-side management (DSM). Transmission system operators who are legally bound to maintain grid stability implement DSM by setting a number of financial incentives to electricity consumers.

We consider two sets of decisions for industrial electricity consumers to exploit these incentives: on top of scheduling production in a way that minimizes electricity cost on the hourly spot market, additional production flexibility can also be sold on balancing markets.

We cover two different scenarios: in the first scenario, the production schedule is formulated as a mixed-integer linear program (MILP) and solved deterministically for varying degrees of operational flexibility. In a non-linear program (NLP) bidding problem, remaining flexibility reserves are offered at optimized ask prices on the balancing market. The goal is to take coordinated actions on the day-ahead and balancing market for a minimization of total energy cost. In the second scenario, we consider a different production model and assume that bidding prices are given. We now add the uncertainty of having to provide balancing power in the scheduling model. We apply methods of robust optimization to determine a cost-minimizing strategy.

2 - Continuous-time Scheduling in Green Supply Chain Management

Wolfgang Albrecht

As companies are predominantly organized in complex network structures due to progressing globalization, an approach for implementing current requirements of ecological sustainability into common business practices can be found in Green Supply Chain Management (GSCM). The proposed optimization models for continuous-time scheduling in GSCM integrate aspects of closed-loop logistics and emissions control for multi-stage networks with multiple sites and different product maturities. In course of bidirectional product transformation, both forward and reverse material flows can occur between adjacent or non-adjacent stages of previous or subsequent production, distribution, recycling, or disposal stages that may be composed in an arbitrary sequence. Different model variants are distinguished regarding product constitution (non-perishable and perishable goods) and recycling type (internal, external, and combined recycling). The continuous-time modeling technique enables to determine start and end times of network-wide operations in 24/7 process industries exactly to the second within a short-term planning horizon of several days. Additional financial balancing merges relevant monetary consequences within discrete liquidity periods while ensuring an appropriate assignment of exactly scheduled operations. Due to the high complexity of the proposed mixed-integer programming models, computational experiments conducted on a high-performance cluster system revealed that problem instances of realistic scope often result in unacceptable computational efforts. However, a large-scale scenario analysis shows that it is possible to generate satisfying solutions in drastically reduced computation times by applying problem-tailored variants of relax-and-fix heuristics.

3 - Customer Order Behavior Visualization and Interpretation

Marco Ratusny, Maximilian Schiffer, Shreya Singh

In operational demand planning and order management, it is essential to understand customer order data to provide insights for supply chain management processes. Herein, recent advances in the semiconductor industry have been leveraged by extracting vital information from vast amounts of data. This new amount of data and information paves the way for developing improved prediction methodologies for customer order behavior (COB), e.g., predicting whether customers overplan their demand to secure their required delivery. Against this background, we develop a general framework to detect and predict COB. We base our work on the data of Infineon Technologies AG, which we use to categorize the underlying COB into predefined patterns. We then show how to devise a sophisticated yet intuitive image-based visualization for the resulting COBs utilizing two-dimensional heat maps. These heat maps allow us to develop two convolutional neural networks (CNNs) to detect 18 different COB patterns in total. To extract the exact behavior for each delivery week and the general behavior over a longer period, we use the CNNs to create 1-delivery-week and 40-delivery-weeks classifications. We show how to utilize both synthetically generated and real customer data to train the CNNs. Integrating synthetically generated data into the training phase allows us to strengthen the inclusion of rare pattern variants that we identified during initial analyses. We then use actual customer data to benchmark our approach and compare the CNNs' results against status-quo benchmark models, e.g., random forests. Our CNN-based approach achieves a 24 to 80 percentage points higher classification accuracy compared to the status quo.

4 - Agent based heterogeneous production equipment coordination in an environmentally oriented production setting

Sebastian Scholz, Frank Meisel

In periods of high renewable energy generation, feed-in management actions are mandatory to restrict the generation of renewable energy to prevent overloads of transmission infrastructure. This means that renewable energy is not generated, although it could have been produced. In our setting, an externally provided signal is used for aligning production and recharging decisions of a company to the occurrence of excessive renewable energy supply to counteract feed-in management actions. Furthermore, industrial companies have to take care of their internal power load management to prevent increases in energy costs. We bring both fields together by (1.) optimizing production scheduling and equipments' recharging decisions such that the internal load management of a company is respected, while (2.) supporting renewable energy usage in a context with feed-in management prevention through increased local consumption in periods of renewable energy peak generation. As a consequence, a company can flexibly adapt its energy demand to the current situation of the renewable energy generation. With this, we enable an eco-oriented Industrie 4.0 perspective. More precisely, we present two optimization models that account for the heterogeneity of different types of production equipment and propose an agent-based production coordination platform (PCP) that coordinates the decision-making. A real world case study is conducted in a stochastic dynamic environment and a sensitivity analysis of the control parameters reveals how the performance of the PCP reacts to different degrees of information availability. In view of the environmentally oriented optimization goal, we finally show that the signal-driven PCP can achieve a substantial reduction of production-related CO2 emissions.

■ TD-12

Thursday, 14:20-15:40 - Faulhorn

Data-Driven Approaches

Stream: Mobility and Traffic
Invited session
Chair: *Jan Fabian Ehmke*

1 - Strategic Planning Support for Road Safety Measures Based on Accident Data Mining

Katherina Meißner, Julia Rieck

Road safety is a major concern nowadays, as accidents kill on average 3,600 people per day. In order to reduce the number of road accidents, various institutions such as the police or local authorities jointly organize and implement actions and measures to increase road safety. The scope, type, and location of road safety measures must be planned at a strategic level several months in advance in order to be fully effective. Therefore, it is necessary to analyze and predict the different circumstances of accidents comprehensively. Only with the knowledge, e. g., about the temporal pattern, locations, conditions of roads or speeds, meaningful actions can be derived and implemented. We propose a framework to support strategic planning of road safety measures that consists of several consecutive data mining stages. The embedded data mining approaches, i. e., frequent itemset mining, time series clustering, time series classification, forecasting, and scoring, are carefully selected, coordinated, and aligned. For this purpose, we present a novel clustering validation index and discuss ways to evaluate the parameter settings for the individual stages. In total, the framework is applied in four different geographical regions. Thereby, actions for road safety are derived for each region and also parameter settings are derived that are particularly suitable for the framework to investigate novel geographic regions. The most interesting accident feature combinations are presented in a comprehensive dashboard.

2 - Estimating the Robustness of Public Transport Systems Using Machine Learning

Alexander Schiewe, Matthias Müller-Hannemann, Ralf Rückert, Anita Schöbel

The planning of public transport systems is a complex process with many different possible objective functions. One important aspect that is not considered often is the system's robustness from a passenger's point of view. Integrating this into the solutions process is very challenging. Even the evaluation of the robustness of a given public transport system is hard due to the large number of possible delay scenarios to consider. In this talk, we will use methods from machine learning to allow for a faster robustness evaluation of public transport systems. By determining possible key features of a line plan, a timetable, a vehicle schedule and a corresponding passenger demand, we train an artificial neural network to predict the results of a set of diverse and time-consuming robustness simulations in constant time. We evaluate the neural network on several benchmark datasets, obtaining a high accuracy of its robustness predictions and using the results for a proof-of-concept local search to improve the robustness of a given public transport system. The local search is able to find competitive solutions very fast, proving the benefits of our presented approach.

3 - Comparison of different prediction methods for fare revenues in public transportation in Berlin

Sandra Spiegelberg, Jonas Krembsler, Nicki Lena Kämpf, Thomas Winter, Nicola Winter, Robert Knappe

We present first results from a case study of fare revenue forecast in public transportation in Berlin. The data is based on monthly fare revenues for different product segments. The results will be used in a research project in public transport with the goal of automating revenue controlling and implementing data-driven decision-making in the existing controlling processes. The focus of this study is to obtain suitable and reliable predictions: on the one hand with autoregressive methods such as ARIMA, SARIMA as well as Holt-Winters Exponential Smoothing and on the other hand with methods that include exogenous variables such as SARIMAX, MLR, LASSO, Ridge, Random Forests, Gradient Boosting, and Neural Networks. The data concerning exogenous variables are freely available and cover a wide range from tourism data to labor market development and weather data. We discuss the different methods and compare the prediction results with common accuracy measures. The goal is to evaluate a wide range of different methods in order to decide in which situations they out- or underperform other methods. Besides simple prediction accuracy, another part of the study is the feature selection and interpretation of their impact. We address automatic feature selection using traditional approaches such as AIC optimization, a rolling window cross-validation approach optimizing the cv-error, and algorithmic approaches such as LASSO or Bayesian optimization. We discuss the interpretability of the results and the advantages and disadvantages of different approaches.

4 - Traveler-Oriented Multi-Criteria Decision Support System for Multimodal Itineraries

Jan Fabian Ehmke, Thomas Horstmannshoff

In recent years, innovative mobility services such as car, bike and ridesharing services have emerged. These contribute to the choice and variety of mobility services available for personal mobility planning. To combine these services into multimodal door-to-door itineraries, travelers expect a diverse set of combined mobility services according to several individual preferences. Although efficient approaches exist to find multimodal shortest paths, the full set of Pareto-optimal travel itineraries cannot be efficiently determined when considering multiple traveler preferences in a large multimodal network. Moreover, traveler-oriented exploration of the search space requires more transparent and explainable decision support in terms of the available options and the complex characteristics of the solution space.

We propose a multi-criteria decision support system for efficient approximation of the Pareto front of multimodal travel itineraries. The core idea is the systematic application of solution space sampling. We focus on the efficient scalability of the sampling framework with respect to multiple preferences of travelers, as well as on the identification of features that allow travelers to better assess the choice of itineraries. The framework is evaluated both from a traveler as well as from a technical perspective in detail using a large amount of real-world data of mobility services. For this purpose, we analyze long-distance travel between major cities in Germany considering up to five traveler preferences simultaneously.

■ TD-13

Thursday, 14:20-15:40 - Blüemlisalp

Human Machine Interaction

Stream: Game Theory and Behavioral Management
Invited session

Chair: *Andreas Fügener*

1 - Queuing systems in the light of skill level and preferences: Evidences from behavioral experiments in automated warehouses

Fabian Lorson, Alexander Hübner, Andreas Fügener

Many studies in behavioral operations have showed that the design and operating policies of queuing systems impact human factors and overall service times, driven by different behavioral mechanisms. For example, queue length or queue design influence overall system performance, but the degree may be different depending on skill level or workstation preference.

Using field experiments in human-machine interactions at advanced workstations in a grocery warehouse, we study the impact of (i) queue length (either high or low workload) depending on skill level (above or below average) and (ii) queue design (either dedicated or pooled queue) depending on workstation type (preferred or undesired). We hypothesize that (i) the performance of below average employees increases more when workload is growing compared to above average employees, as the intrinsic motivation of above average employees may be higher. Additionally, we hypothesize that (ii) dedicated queues improve productivity at undesired workstations, mainly due to increased engagement and social speedup pressure.

The insights generated of the behavioral experiments will shed light onto optimal queue setups, and enrich the theoretical discussion on behavioral human-machine interactions.

2 - Keep It Mystic? - The Effects of Algorithm Transparency on the Use of Advice

Cedric Lehmann, Christiane Haubitz, Andreas Fügener, Ulrich Thonemann

Algorithmic decision support is omnipresent for many managerial tasks where human judgment makes the final call. However, the lack of transparency of algorithms is often stated as a barrier of successful human-machine collaboration. In this paper, we analyze the effects of algorithm transparency on the perceived value of algorithmic advice and its resulting utilization for a simple, easy-to-understand algorithm.

In a laboratory experiment, participants received algorithmic advice for a forecasting task. Only the treatment group was informed about the underlying principles of the simple yet optimal advice-giving algorithm. While the explanation increased the understanding of the algorithmic procedure, it reduced the perceived value of the algorithmic advice, its utilization, and the participants' performance.

Our results indicate that the effects of algorithm transparency on the use of algorithmic advice are not straightforward, and that transparency might even be harmful. Going forward, we plan to explore whether algorithm complexity moderates this effect.

3 - Contextual information in the forecasting support systems

Anna Sroginis, Nikolaos Kourentzes, Robert Fildes

Taking into account both types of information: model-based (quantitative) and contextual (qualitative) can provide many benefits for a decision-maker. But most Forecasting Support Systems (FSS) do not record or structure any qualitative statements, and the whole process is usually challenging to track and evaluate. We analyze how forecasters use textual information to adjust statistical sales forecasts. We developed a forecasting experiment where qualitative information is provided either in a step-by-step fashion, decomposing the information by source, or simultaneously, allowing us to contrast the effects of different forms of visual support which is crucial for forecasting practice and the design of FSS.

4 - Incentive Study on Strategic Behaviors to Resource Sharing on P2P Networks

Yukun Cheng, Xiaotie Deng

The booming sharing economy has a common challenge in its eventual success: How to motivate the participating agents to take truthful actions out of own interests. Our incentive study has focused on the agents' behaviors in resource sharing on P2P networks. P2P networks are based on a distributed protocol where agents make their own decisions based on local information, actions of their own neighbors. Early works have modeled a tit-for-tat strategy as a proportional response protocol, and shown that the dynamics of such a protocol converges to a market equilibrium. We first develop an array of truthfulness results of the proportional response protocol against different deviations in the forms of the weight cheating strategy and edge deleting strategy. However, it is shown that the proportional response protocol is not truthful against the Sybil attacks where an agent may split its resource among its different copies. As a remedy for this untruthful property under the Sybil attack, the incentive of any agent has been shown to generate a limited gain for an agent pursuing such an attack under several special networks. Such a limited gain is characterized by the incentive ratio, which is defined as the factor of the largest possible utility gain that an agent can achieve by behaving strategically, given that all other participants. We proved that the incentive ratio of proportional response protocol against the Sybil attacks is exactly two on trees, exactly $\sqrt{2}$ on cliques, and exactly 2 on rings. Recently, we conclude a complete study on agent incentives by proving a tight incentive ratio of two for any agent launching the Sybil attack on any networks.

■ TD-14

Thursday, 14:20-15:40 - Wetterhorn

Prescriptive Analytics and Interpretability

Stream: Analytics
Invited session
Chair: *Philipp Baumann*

1 - An a-priori Parameter Selection Approach to Enhance the Performance of Genetic Algorithms Solving Pickup and Delivery Problems

Cornelius Rüther, Shabanaz Chamurally, Julia Rieck

Solving pickup and delivery problems with, e. g., multiple depots, time windows, and heterogeneous vehicle fleets contains many real-world restrictions and is therefore a challenging routing task. Due to its complexity, a Genetic Algorithm with sufficiently good solution quality is recommended here. Genetic algorithms contain multiple operators that are called with certain probability parameters. However, the selection of these parameters strongly depend on the data structure of the given instances. Hence, selecting the best parameter configuration for each new instance is a natural problem to enhance the overall solution quality.

We present an a-priori parameter selection approach based on classifying new instances to clusters for which an appropriate parameter configuration is determined. In doing so, reasonable features describing sufficiently the structure of the problem instances are developed in order to specify suitable clusters. A Bayesian Optimization approach with Gaussian Processes is then used to find the best parameters for each cluster. For new problem instances which are classified to certain clusters, the parameter configuration associated with the considered cluster is used.

The a-priori parameter selection is evaluated on four well-known pickup and delivery problem data sets, each with 60 instances and different numbers of depots. It is shown that the parameter selection approach is a good choice in improving the performance of the considered genetic algorithm over all problem instances in each data set. Additionally, the best parameter configuration per problem instance class is able to enhance both the frequency of finding the best solution as well as the relative error to this solution significantly.

2 - Mathematical Optimization for Individual and Group Level Counterfactual Explanations

Jasone Ramírez-Ayerbe, Emilio Carrizosa, Dolores Romero Morales

Post-hoc explanations of machine learning models are crucial to be able to understand and explain their behaviour, and thus enhance transparency and fairness. An effective type are counterfactual explanations, i.e., minimal perturbations of the predictor variables to change the prediction for an individual instance. Different counterfactual explanations can be obtained depending on the distance used to measure the changes. We propose a multi-objective mathematical formulation to obtain individual level counterfactual explanations for state-of-the-art machine learning models based on scores. This includes tree ensemble classifiers as well as linear models such as Support Vector Machines. In addition, we formulate the problem of obtaining group level counterfactual explanations for a given subset of instances. We will illustrate our method using real-world data.

3 - A new Greedy Heuristic driven by Machine Learning for the symmetric Traveling Salesman Problem

Umberto Junior Mele, Luca Maria Gambardella, Roberto Montemanni

Recent systems applying machine learning to solve the Traveling Salesman Problem (TSP) exhibit issues when scaled up to real case scenarios. If good results are shown for small instances, these systems struggle to generalize to larger problems as classic heuristics do. The main reason could be attributed to the data mismatch between different size instances.

The use of candidate lists to address large problems with machine learning has been recently proposed. The candidate lists select for each city in the TSP a smaller set of promising ones, that are likely to be inserted in the optimal tour. Such pre-processing procedure allows to restrict the searching space, consequently reducing the solver computational burden. In this context, machine learning were engaged to create candidate lists and not to actively produce TSP solutions.

Instead, motivated by exploratory and statistical studies, we construct actively a partial solution for the TSP employing machine learning. We use it to confirm the insertion in the solution just for high probable edges using their candidate lists as input. This strategy enables a better generalization and creates an efficient balance between machine learning and searching techniques. Our ML-greedy heuristic is trained on small instances. Then, it can produce solutions to large problems as well without losing quality. We compare our results with classic heuristics, showing good performances for TSPLIB instances up to 1748 cities. Although our heuristic exhibits an expensive constant time operation, we show acceptable time complexity during the construction phase after training.

4 - Predicting Inventory Inaccuracies to Minimize Record-Keeping Errors

Defne Eskiocak, Buse Mert, Birol Yüceoglu

In FMCG retailing, inventory accuracy is essential to increase customer satisfaction, revenue and to smooth operational processes, such as procurement. Physically keeping excess inventory due to inaccuracies in digital records leads to an increase in cost. Similarly, keeping low inventory causes lost sales and customer dissatisfaction. In this work, we aim to use machine learning to predict product categories with high inventory record-keeping errors. By using the experience of the field team, we examine the transactions related to the inventory and sales to generate several features related to product movements, previous record-keeping errors and product attributes. With the aid of machine learning, these features are used to predict the categories with a high probability of having inaccurate inventory. As a result of our predictions, we ensure that monthly audits are made with the support of the field team for categories with high probability of error and the actual and digital inventories are synchronized. The product category recommendations are specific to each store as opposed to the previous approach where each store is given the same product categories.

■ TD-15

Thursday, 14:20-15:40 - Silberhorn

GOR Master Thesis Awards

Stream: PC Stream
Sponsored session
Chair: *Kevin Tierney*

1 - A semidefinite approach for the single row facility layout problem

Jan Schwiddessen

The single row facility layout problem (SRFLP) is the strongly NP-hard optimization problem of arranging n facilities of given lengths on a straight line, while minimizing a weighted sum of distances between all facility pairs. We review different existing lower bounding techniques for the SRFLP based on linear and semidefinite programming and propose a new semidefinite approach for the SRFLP. The semidefinite relaxations are solved by an algorithmic method not yet considered for the SRFLP and we demonstrate the improvements to current techniques that our novel approach has. Finally, we address the use of our semidefinite bounds within a branch-and-bound approach, and provide some useful tools such as primal heuristics and branching rules.

2 - An Adaptive Large Neighborhood Search for a Real-World Multi-Attribute Vehicle Routing and Scheduling Problem

Pia Ammann

The efficiency of transportation can be improved by applying intelligent optimization methods to solve complex routing and scheduling problems arising in practice. We present an Adaptive Large Neighborhood Search for a tightly constrained Vehicle Routing and Scheduling Problem, in which an unlimited heterogeneous fleet of vehicles can perform multiple trips to satisfy the demand in a split delivery vehicle routing problem with time windows. In addition to commonly applied destruction heuristics, multiple new destroy operators for shifting entire routes and splitting nodes are introduced. Based on an extensive numerical study including test and real-world instances, the effectiveness of the proposed approach to find near-optimal solutions within a limited time span is demonstrated. By tolerating some level of infeasibility, we further improve the results considerably. Today, our algorithm is deployed at one of Europe's largest intercity bus network providers to compute efficient routes and schedules for buses transporting passengers all over Europe.

3 - SAT-Heuristics for the Periodic Event Scheduling Problem

Sarah Roth

The thesis focuses on investigating the prospects of transforming the Periodic Event Scheduling Problem (PESP) into a Boolean formula so that it can be solved as a satisfiability problem (SAT). The main advantage of this approach is the possibility to use a SAT-Solver which enables us to find feasible solutions with impressive speed. The PESP is introduced in the context of periodic timetabling in a public transport network with the aim to minimize the total travel time of the passengers. It is distinguished between the decision and the optimization version of the PESP. While PESPdec only asks for a feasible timetable, PESPopt requires a timetable that is optimal. The investigated transformation from PESPdec to SAT is based on covering an area of infeasible points with rectangles. One main contribution is the definition of such a covering as an optimization problem which is then solved with concrete coordinates. Furthermore, there is an optimization version of SAT called MaxSAT. The transformation of PESPopt to a weighted partial MaxSAT enables us to use state- of-the-art MaxSAT-Solvers for solving PESPopt. Modern solution methods for MaxSAT are mainly based on iteratively calling a SAT-Solver. They modify the working formula according to unsatisfiability cores which are returned when the SAT-Solver decides that an instance is "unsatisfiable". A connection between these unsatisfiability cores of a MaxSAT instance and the cycle periodicity constraints in the network of the original PESPopt instance is established. Finally, new heuristics based on iterative calls to a (Max-)SAT-Solver are presented. The most competitive of these heuristics outperforms the state-of-the-art MIP-Solver SCIP on large instances within a fixed run time of 60 min. On the most complex instances of the test set, it is even able to find a timetable whose objective value has about half the size of the output of SCIP. This result can be improved even further, when letting these two solution methods run in parallel and admitting them access to a shared solution pool.

4 - Risk Aware Flow Optimization and Application to Logistics Networks

Erik Diessel

Supply chains are increasingly faced with various uncertainties threatening the flow of materials. Thus, improving their resilience is essential.

In this talk we consider an adjustable robust optimization problem: given a set of suppliers and demand nodes with arc and node capacities, we wish to find a flow that is robust with respect to failures of the suppliers. The objective is to determine a flow that minimizes the amount of shortage in the worst-case after an optimal mitigation has been performed. An optimal mitigation is an additional flow in the residual network that mitigates as much shortage at the demand sites as possible. We describe the mathematical formulation of the corresponding robust flow problem with three stages where the mitigation of the last stage can be chosen adaptively depending on the scenario. For optimizing with respect to this NP-hard objective function, we develop three algorithms. Namely an algorithm based on iterative cut generation usable with scenario sets in implicit form, a simple Outer Linearization Algorithm, and a Scenario Enumeration algorithm. We compare with numerical experiments the practical efficiency of these methods.

In an outlook we describe an extension of this approach towards robust multicriteria optimization. We compare various theoretical concepts for incorporating robustness in multicriteria problems and their use cases for supply chain design.

■ TD-16

Thursday, 14:20-15:40 - Schilthorn

Logistics in Health Care

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

1 - Fairness and Efficiency - Incompatible Objectives in EMS Location Planning?

Matthias Grot, Luis Nagel, Tristan Becker, Pia Mareike Steenweg, Brigitte Werners

When designing emergency medical systems, the fairness of the provided service is an important goal. Each patient should have equal access to fast and qualified care by emergency medical services (EMS). In metropolitan areas, the heterogeneous distribution of demand constitutes a challenge for fair ambulance location planning. Many EMS location models focus on efficiency criteria, such as coverage measures. However, it requires less resources to cover densely populated city centers compared to suburban districts. Thus, an unequal service availability in metropolitan areas with a heterogeneous distribution of demand results when coverage measures are maximized. To provide further decision support, we extend a recent location planning model by the well-known Rawlsian criterion and by the Gini coefficient, respectively. Thus, the potentially conflicting criteria efficiency and fairness are simultaneously considered. Generating the Pareto frontiers shows that it is possible to improve fairness considerably by giving up only a small amount of total coverage. We therefore recommend the integration of fairness criteria into EMS location models.

2 - Classifying ready-for-transfer patients in the intensive care unit based on clinical data

Franz Ehm, Volkmar Franz, Maic Regner, Udo Buscher, Hanns-Christoph Held, Peter Spieth

In the intensive care unit (ICU), a limited number of beds and personnel are available for the treatment of the most severely sick patients. In the event of new arrivals physicians often have to decide upon patients who are ready to go to a lower ward and thereby free up capacity. The choice is complicated as it depends on numerous clinical and operational factors and comes at the risk of causing negative patient outcome. Clinicians at Uniklinikum Dresden (UKD) expressed their need for a data-driven decision support when identifying ICU patients for transfer. For this purpose we build a mathematical classification model that is trained on historical clinical data to evaluate actual patient information. Patient outcome is labelled according to readmission to the ICU within 72 hours following discharge. The transfer decision is then modelled as a classification problem which predicts the event of readmission. Our research is based on clinical data from a total of 41108 episodes providing information on transfer history, patient characteristics, vital parameters and treatments. In a first step, relevant features for transfer are specified by expert clinicians at UKD. We use these as a guideline to construct a first classifier which employs a specific threshold value of the number of critical parameters in a patient to predict her chance of readmission. In a next step, logistic regression models are deployed using binary variables from critical parameter counts as well as metric features from measurements, scores and patient data. Performance of the trained classifiers is evaluated on a test set using accuracy metrics as well as the receiver-operating-characteristic.

3 - The use of drones in healthcare logistics

Melanie Reuter-Oppermann

Unmanned aerial vehicles, i.e. drones and VTOLs, are finding their way into research as well as practice, especially in the areas of security and healthcare. Their use is particularly promising when conventional road transport is not possible or would take too long. Drones could be used to transport equipment, medication or vaccines, while VTOLs could even bring paramedics to an emergency or transport patients to a hospital. After a short overview of potential use cases, the transport of automated external defibrillators (AEDs) and blood products will be discussed. In the event of an out-of-hospital cardiac arrest, resuscitation must be started as quickly as possible. Often, ADEs are located inside buildings or too far away and cannot be found fast enough by first responders or volunteers. Drones could take AEDs to incidents before an ambulance arrives to save valuable time. Location models can be used to determine base locations for the drones in order to reach as many patients as possible and/or maximise survivability. Timely transport of blood products can be especially challenging in rural areas. So far, blood products can hardly be produced artificially, which is why healthcare systems have to rely completely on volunteer blood donations. In addition, blood products have a short shelf-life. In many countries, it is already challenging to fulfil the everyday demand. Then, it is neither possible nor efficient to store blood products at every demand location in large quantities. Drones could be used to transport blood products to remote locations or to meet short-term demands. Operations research models can determine locations for drones and schedule their routes.

Thursday, 16:00-17:00

■ TE-01

Thursday, 16:00-17:00 - Bundeshaus

Plenary talk Perakis

Stream: PC Stream
Sponsored session
Chair: *Georgia Perakis*

1 - Analytics for tackling Covid-19
Georgia Perakis

In this talk I will discuss how Analytics have helped for tackling the COVID-19 pandemic. I will present work from various groups but will mostly focus on the work of my team related to COVID-19 this past year. I will discuss the MIT-Cassandra model that is a suite of models that are part of an ensemble method for COVID-19 case and death prediction. I will discuss the individual methods and what motivated them and then the ensemble method and show how they perform with data in the US. I will discuss how these models are comparing relative to other models also used by the CDC. I will further connect these predictions with detecting true infection (also referred to as prevalence). Finally, I will discuss how these methods and results can be used to distribute vaccines in different counties (or areas) within a state (or country) to a heterogeneous population, through optimization, ensuring fair distribution among the different counties. We will show how the proposed optimization model performs in the different counties in the state of Massachusetts. (The MIT-Cassandra team includes in addition to myself my students (current and former): Amine Bennouna, David Nze-Ndong, Boyan Peshlov, Divya Singhvi, Omar Skali-Lami, Yiannis Spantidakis, Leann Thayaparan, Asterios Tsiourvas, Shane Weisberg)

Thursday, 17:00-18:00

Friday, 9:00-10:20

■ FA-04

Friday, 9:00-10:20 - Eiger

Data Reduction

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Andreas Alpers*

1 - Power-SLIC: Generating Superpixels via Clustering
Maximilian Fiedler, Andreas Alpers

Superpixel algorithms, which group pixels similar in color and other low-level properties, are increasingly used for pre-processing in image segmentation. Motivated by improving superpixel compactness, we propose a new superpixel generation method called Power-SLIC. We compute an anisotropic power diagram whose cells result in the superpixel partition. The optimization algorithm exploits a strong relationship between optimal pixel assignments and diagrams. For applications requiring fast computation, we propose a heuristic to approximate the underlying discrete optimization problem. Moreover, we employ coresets to speed up superpixel generation for high-resolution images significantly. On the BSDS500 data set, Power-SLIC outperforms other state-of-the-art algorithms in terms of compactness and boundary precision, and its boundary adherence is the most robust against varying levels of Gaussian noise. In terms of speed, Power-SLIC is competitive with SLIC.

2 - On representing polycrystalline microstructures by generalized balanced power diagrams
Andreas Alpers, Andreas Brieden, Peter Gritzmann, Allan Lyckegaard, Henning Friis Poulsen

Polycrystalline materials such as metals, alloys and most ceramics are widely used in many industrial applications. Their physical, chemical and mechanical properties are to a large extend governed by the structure of the individual crystals inside. In this talk we will introduce the concept of generalized balanced power diagrams (GBPDs) as a concise alternative to voxelated mappings that are traditionally used to represent the crystals. In GBPDs, each crystal is represented by (measured approximations of) its center-of-mass position, its volume and, if available, by its second-order moments. GBPDs generalize Voronoi and power diagrams, and we will show how they can be computed by solving instances of weight-balanced least-squares assignment problems.

3 - Adding Relations in Multi-levels of a Complete K-ary Linking Pin Organization Structure Maximizing Total Shortening Distance
Kiyoshi Sawada

This study proposes a model of adding relations between all members of each level of multi-levels in a complete K-ary linking pin organization structure where every pair of nodes which have the same parent in a complete K-ary tree is adjacent. When edges are added between every pair of nodes with the same depths in L levels of a complete K-ary linking pin organization structure of height H, the total shortening distance which is the sum of shortening lengths of shortest paths between every pair of all nodes by adding edges is formulated. An optimal set of depths of L levels is obtained by maximizing the total shortening distance.

4 - A new approximation algorithm with a posteriori performance guarantee for solving the Facility Location Problem
Alexandr Shtepa, Edward Gimadi

The unsplittable Facility Location Problem (FLP) without triangle inequality is well-known discrete facility location problem. This problem is NP-hard [Garey, Johnson, 1979]. We present an approximation primal algorithm with the running time O(m n log m) and compare it with the approximation algorithm with a posteriori performance guarantee on oversized input date.

■ FA-05

Friday, 9:00-10:20 - Mönch

Semidefinite Programming

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Elisabeth Gaar*

1 - BiqBin: a solver for binary quadratic problems subject to linear constraints
Nicolo Gusmeroli, Angelika Wiegele

Binary quadratic problems (BQP) are very general and have several applications in different fields. In order to solve these problems we use EXPEDIS, an exact penalty method over discrete sets which transforms a linearly constrained BQP into a max-cut instance.

We present this algorithm, which penalizes the equality constraints and makes use of a penalty parameter obtained by solving some semidefinite program. This method also provides a threshold parameter, from which it is possible to determine whether the original problem is feasible.

The final max-cut reformulation is solved by BiqBin with a branch-and-bound algorithm. In the bounding procedure we use a semidefintite relaxation, thus explain how to add high-order odd clique with potentially large violation in the relaxed problem.

We compare the performance of our solver with some of the currently best solvers available, e.g., BiqCrunch, Gurobi and CPLEX, showing the efficiency of our method.

2 - SDP relaxations for certain mixed-integer quadratic problems
Shudian Zhao, Angelika Wiegele

This presentation will talk about bounds for the k-equipartition problem and certain problems with cardinality constraints via semidefinite programming (SDP). In the first part, we will show a tight SDP relaxation with nonnegativity constraints for k-equipartition. To tackle the difficulty of solving large instances with nonnegativity constraints, we use the extended alternating direction method with multiplier (ADMM). This method can solve the SDP problems efficiently. We alsao apply heuristics using the SDP solution to obtain an upper bound for the k-equipartition problem. In this way, we can find upper bounds with good quality with little computational expense. In the second part, we give another evidence for the strong modeling power of SDP by considering problems with cardinality constraints.

3 - Taking advantage of SDP in a Graph Theory Conjecture
Elisabeth Gaar

In 1968 Vizing conjectured that the product of domination number of two graphs is always smaller or equal to the domination number of the product graph. Today, we still don't know whether this conjecture is true or not.

In this talk we will investigate a new way of tackling Vizing's conjecture and discuss recent results. This approach starts by building an algebraic model of the conjecture with some parameters. Then it translates Vizing's conjecture for these parameters into the question of whether a specific polynomial is nonnegative over a specific ideal. Then the approach does another reformulation to the question of whether a specific polynomial is a sum-of-squares polynomial on a certain level of the sum-of-squares-hierarchy. Finally it uses semidefinite programming (SDP) to answer these kind of questions. We will give insight in the recent methods that have been used for developing new sum-of-squares certificates for particular parameters and give an answer to the question of whether an open conjecture from the literature on certain certificates is true.

4 - New Sum-Of-Squares Certificates for Vizing's Conjecture
Melanie Siebenhofer, Elisabeth Gaar

Vizing's conjecture is an open famous graph-theoretical problem stated in 1968 by the mathematician Vadim Vizing. It claims that the domination number of the cartesian product graph of two graphs G and H is at least as large as the product of the domination numbers of G and H.

In 2019 Gaar, Krenn, Margulies, and Wiegele presented a new method to potentially prove the conjecture. Their approach is based on ideal theory and semidefinite programming. More precisely, they reformulated Vizing's conjecture as a sum-of-squares problem for graph classes with fixed number of vertices and minimum dominating sets. They successfully derived sum-of-squares certificates for some graph classes with high domination numbers.

In this talk, we consider their approach for graph classes with domination number 1. We can derive the reduced Gröbner basis for this particular case, which allows us to state the minimum degree of a sum-of-squares certificate for Vizing's conjecture. We further present a method to find certificates for these graph classes, which is again based on solving semidefinite programs.

■ FA-06

Friday, 9:00-10:20 - Jungfrau

Theory and Applications of IPs

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Ralf Borndörfer*
Chair: *Renke Kuhlmann*

1 - A Heuristic-Based Reduction for the Temporal Bin Packing Problem with Fire-Ups

John Martinovic, Nico Strasdat

Given the ever-increasing role of data centers in global energy consumption, the problem of efficiently assigning jobs (items) to servers (bins) has become more and more important in recent years. In this framework, we consider the temporal bin packing problem with fire-ups (TBPP-FU) which requires to assign jobs having time-dependent resource demands to homogeneous servers of given capacity. In the light of energy efficiency, not only the number of necessary servers but also their operating mode (represented by the number of switch-on processes, so-called fire-ups) has to be reflected in the objective function. Hence, both criteria are typically addressed by a standard weighted-sum method, but the resulting ILP models turn out to be challenging in size. For this reason, various tailored reduction strategies can be applied to obtain more tractable formulations. As a main contribution, we will show how the information from a heuristic solution can be used to further improve these exact approaches, extending a theoretical result that was previously proven only for very small choices of the weighting parameter in the literature. Finally, the benefits of this new reduction procedure will be demonstrated based on computational tests.

2 - New exact approaches for the combined cell layout problem

Anja Fischer, Mirko Dahlbeck, Philipp Hungerländer, Kerstin Maier

In this talk we consider the Combined Cell Layout Problem (CCLP), an important class of facility layout problems, which has several practical applications and in which one combines several Single-Row Facility Layouts and Directed-Circular Layouts. A well-known special case of the CCLP is the Multi-Bay Facility Layout Problem (MBFLP). Given a set of cells of type single-row or directed-circular and a set of one-dimensional departments with pairwise transport weights between them, the CCLP asks for an assignment of the departments to the cells such that departments in the same cell do not overlap and such that the sum of the weighted center-to-center distances is minimized. Distances between departments in the same cell are measured according to the layout type of the cell and otherwise their distance equals the sum of the distances to the associated (un-) loading stations of the cells plus possible space between the cells. We solve the CCLP exactly by enumerating over all assignments of the departments to the cells and solving several CCLP with fixed-cell assignment using well-known models from the literature. We show that in many relevant cases the number of row assignments that has to be considered can be reduced significantly by merging two cells of type single-row. Partially some dummy departments have to be added to the cells in order to handle varying inter-cell distances. This leads to new well-performing exact approaches for the CCLP and the MBFLP. We present computational results for instances with up to six cells. Additionally, we compare the optimal objective values of several layout problems from a theoretical and a practical point of view.

3 - Variants of the Dial-a-Ride Problem encountered by Austrian mobility providers

Philipp Armbrust, Kerstin Maier, Veronika Pachatz, Philipp Hungerländer

The Dial-a-Ride Problem (DARP) consists of defining a set of routes that satisfy transportation requests. A request consists of a pick-up location, where one or many passengers get on the vehicle, a drop-off location, and further restrictions, namely time windows and capacity constraints. A common example arises in door-to-door transportation of people and in our work, we focus on elderly people or people with impaired mobility. We consider a dynamic-deterministic variant of the DARP for two Austrian mobility providers. The focus of these operators lies on rural regions served by a heterogeneous fleet of vehicles and as an additional condition, we take the capacity of wheelchairs into account. We consider a heuristic and an exact solution approach for the DARP, namely a Large Neighborhood Search and a Mixed-Integer Linear Programming approach. In a computational study, we show different operator scenarios, including minimization of overall driven kilometers, number of used vehicles, and number of unscheduled requests, with up to 500 requests per day and 30 vehicles.

4 - Optimal Districts for Transit Network Control

William Surau, Ralf Borndörfer, Stephan Schwartz

In this talk we consider an application from German toll control. One method for toll control enforcement is the use of mobile teams. Every team can cover only a certain area of the transit network in one shift. Areas with high traffic should be controlled more frequently. This motivates the problem of finding an optimal covering of the transit network with districts, i.e., length restricted connected subgraphs, where each district has within itself homogeneous traffic. We propose a column generation approach where the pricing problem generates promising districts. The pricing problem turns out to be a variant of the NP-hard Maximum Weight Connected Subgraph Problem. It is solved as an integer program and supported by different heuristics. Their impact is shown in a computational study on real world instances from German toll control.

■ FA-07

Friday, 9:00-10:20 - Niesen

Machine Learning & Optimization

Stream: Discrete and Combinatorial Optimization, sponsored by FICO
Invited session
Chair: *Charlie Vanaret*

1 - Boosting Frank-Wolfe by Chasing Gradients

Cyrille Combettes

The Frank-Wolfe algorithm is a popular algorithm for constrained optimization. It does not require projections onto the constraint set and has been applied to a variety of real-world problems. Its main drawback however lies in its convergence rate, which can be excessively slow due to naive descent directions. We propose to speed up the Frank-Wolfe algorithm by better aligning the descent directions with that of the negative gradients, while preserving the projection-free property. Although the approach is reasonably natural, it produces very significant results. We demonstrate its competitive advantage over the state-of-the-art in a series of computational experiments.

2 - Evaluating the Potential of Reinforcement Learning and Deep-Q-learning for a Stochastic Scheduling Problem

Mohammed Majthoub Almoghrabi, Guillaume Sagnol

Finding good policies for stochastic machine scheduling problems is hard. Therefore, in this paper our goal is to evaluate the potential of Reinforcement Learning and Deep Q-Learning for stochastic machine scheduling problems. We consider three different types of scheduling problems where the jobs are either processed on parallel machines, related machines, or unrelated machines. Further, we consider a general objective function that contains the most common problems, like minimizing the expected makespan, weighted job tardiness, or weighted machines tardiness as special cases. We model our problem as a Markov decision process and we implement a reinforcement learning method in Python based on Deep Q-learning, which is a hybrid algorithm for determining the optimal policy between Q-learning and Deep-learning. The neural network is trained with several scenarios based on real-world instances. Additionally, we implement several heuristic algorithms that solve the problem. We compare the performance of the policy learned by the neural network with the values of these heuristics. Further, we use the values from the heuristic algorithms to improve the learning process of the neural network.

3 - Ecole: A Library for Learning Inside MILP Solvers

Didier Chételat

It is quite common in applied settings for combinatorial optimization problems to be solved repeatedly with small variations. Solvers traditionally treat every new problem as novel, with no memory of the solving of past instances. This state of affairs had led to a surge of interest, both within academia and industry, in using machine learning methods to take advantage of the statistical relationships between recurrent problems and improve solving efficiency. However, MILP solvers are intricate pieces of software, and so far applications of machine learning methods to these solvers have been large engineering efforts that are impractical for industry.

In this talk we present Ecole, a new open-source C++ and Python library that aims to simplify the development of machine learning methods in exact solvers. It offers a clean API, modeled on the well-known OpenAI Gym machine learning library, to interface with SCIP, a state-of-the-art open-source solver. Ecole is simple, brings a natural separation between solver code and machine learning code, is well-tested and offers sensible defaults. This makes development faster, improves reproducibility, reduces bugs and makes projects that would have required a large team of experts feasible with less resources, perhaps a single data scientist. We hope it will help democratize and simplify research and development in this area, in order to disseminate recent machine learning advances for exact combinatorial optimization to the widest audience possible, both in academia and in industry.

4 - An Image-based Approach to Detecting Structural Similarity Among Mixed Integer Programs

Marco Lübbecke, Mark Karwan, Chase Murray, Zachary Steever, Junsong Yuan

Operations researchers have long drawn insight from the structure of constraint coefficient matrices (CCMs) for mixed integer programs (MIPs). We propose a new question: Can pictorial representations of CCM structure be used to identify similar MIP models and instances? In this talk, CCM structure is visualized using digital images, and computer vision techniques are employed to detect latent structural features therein. The resulting feature vectors are used to measure similarity between images and, consequently, MIPs. An introductory analysis examines a subset of the instances from strIPlib and MIPLIB 2017, two online repositories for MIP instances.

Results indicate that structure-based comparisons may allow for relationships to be identified between MIPs from disparate application areas. Additionally, image-based comparisons reveal that ostensibly similar variations of an MIP model may yield instances with markedly different mathematical structures.

■ FA-08

Friday, 9:00-10:20 - Stockhorn

Power networks

Stream: Energy and Environment
Invited session
Chair: *Christian Füllner*

1 - Developing Minimum-Cost Expansion Plans: A Computation Study of a German Power Distribution Network

Sascha C Burmeister, Guido Schryen

As energy transition promotes decarbonization and electrification, new technologies such as electric vehicles, heat pumps, or photovoltaic systems proliferate. Increased penetration forces distribution network operators to adjust their distribution networks and plan the reinforcement of their infrastructure, including lines and transformers. Recent studies provide minimum-cost expansion plans for aggregated medium-voltage distribution networks. However, details of low-voltage distribution networks have been neglected although they are predominately affected by the energy transition. We aim to close this gap by considering the medium- and low-voltage distribution network in an integrated way and adopting a detailed perspective. We suggest a linear optimization model to develop minimum-cost expansion plans for power distribution network. We demonstrate the applicability of the model by (1) instantiating it with a real German power distribution network and solving the resulting problem instance with a state-of-the-art solver, and (2) using the derived solution in a power flow simulation to ensure its value in practice. Our computational study reveals the importance of considering reinforcements of infrastructure in low-voltage distribution networks in order to respond to the increasing availability and integration of new technologies in the future. Our approach also supports practitioners, such as distribution network operators, to plan the expansion of their distribution networks at minimum costs and to account for network sustainability in terms of adaptability to account for changing loads. We also show limitations of our approach and provide impulses for future research.

2 - Semidefinite Programming Approach to Security Constrained Optimal Power Flow with FACTS Devices

Bartosz Filipecki, Christoph Helmberg

Producing accurate and secure solutions to the Optimal Power Flow problem becomes increasingly important due to rising demand and share of renewable energy sources. To address this, we consider a Security Constrained Optimal Power Flow model with additional decision variables associated with line switching and FACTS devices, such as phase-shifting transformers (PSTs) and thyristor-controlled series capacitors (TCSCs). We show how a Lasserre hierarchy can be applied to this model to obtain a semidefinite programming relaxation. Moreover, we consider efficient method of addressing the contingency constraints. Finally, we provide results of numerical experiments on this relaxation.

3 - Potential-Driven Network Flows under Uncertainty

Rüdiger Schultz

Potential-driven network flows are extensions of classical flows in power, gas, or water supply, that depend on the differences of potentials at incident nodes. Typically, this dependence is nonlinear and associated with every network arc. In the talk, handling this nonlinearity by analytical and algebraic means is discussed. For the nomination validation problem in steady-state passive gas nets with uncertain load the role of potential-driven flow in calculating the probability of feasible nominations is highlighted.

4 - Multitask learning for data-driven wind farm management and condition-based maintenance

Angela Meyer

While the global wind power capacity is undergoing a strong growth, the profit margins for wind farm operators are shrinking in increasingly competitive electricity markets. The condition-based maintenance of wind turbines offers a cut in O&M expenses by reducing on-site inspections and unplanned maintenance work. Modern wind turbines are equipped with comprehensive sensing technology to enable 24x7 remote condition monitoring. Analyzing this sensor data facilitates the automated detection of incipient faults and asset underperformance. This study introduces multitask machine learning models which enable the automated monitoring of wind turbine operation and the detection of anomalies. In doing so, this works supports condition-based maintenance decisions by facilitating an early informed planning of inspection and repair, and thus helping to prevent cost and downtime due to severe subsequent damage. This work introduces multi-target machine learning regressions to provide a more efficient and accurate approach for the simultaneous monitoring of wind turbine subsystems. We demonstrate that early faults in the powertrain can be detected based on component temperatures logged in the turbines' supervisory control and data acquisition systems. We analyze the detection accuracy and detection delays based on multiple machine learning models of the normal turbine operation. Our results demonstrate that multi-target normal operation models match and may even exceed the detection accuracy and detection delay of single-target methods. The proposed multitask learning approach can substantially reduce the life-cycle management cost of automated condition monitoring and thus support condition-based maintenance strategies of wind farm owners and operators.

■ FA-09

Friday, 9:00-10:20 - Gantrisch

Exact Vehicle Routing and Scheduling

Stream: Logistics and Freight Transportation
Invited session
Chair: *Katrin Heßler*

1 - A Branch-and-Price algorithm for the electric freight vehicle scheduling problem

Patrick Klein, Maximilian Schiffer

Electric Commercial Vehicles (ECVs) constitute a promising alternative to conventional internal combustion engine vehicles as they allow for (locally) emission-free operations and may reveal economic benefits resulting from low operational cost. However, realizing economically worthwhile ECV operation remains challenging as often sparse charging infrastructure and long recharging times limit recharging operations to the depot. Here, ahead of time scheduling is necessary to guarantee charger availability. Potential cost savings through time-varying energy prices and deaccelerated battery degradation further complicate this planning problem. This talk formalizes and solves the arising scheduling problem. For this purpose, we model the problem on a time-expanded network and develop an exact branch and price algorithm based on a set partitioning formulation. The pricing problems constitute an extension to the fixed-route vehicle charging problem, introducing time windows and energy cost. We propose a labeling algorithm to solve the resulting shortest path problem. Our approach outperforms state-of-the-art integer programming solvers on a large set of benchmark instances. We further assess the impact of specific instance parameters, e.g., fleet size, planning horizon length, on our algorithm's performance. Our study confirms the scalability of our algorithm. Finally, we show the impact of depot charge scheduling on a fleet operator's overall cost for realistic instances.

2 - A decomposition approach for a joint locomotive and driver scheduling problem in rail freight traffic

Jonasz Staszek, Andreas Bärmann, Alexander Martin

In this work, we consider the joint scheduling of locomotives and their drivers in rail freight companies. Our focus is to compute an optimal assignment of locomotives and drivers to the trains listed in a given order book. This leads to the combination of a set-packing problem with compatibility constraints and a multi-commodity-flow problem. We develop a binary programming formulation to model the given task and improve it by performing a clique-based tightening of the original set-packing inequalities as well as a commodity aggregation for the multi-commodity-flow part. To handle the complexity of the integrated driver and locomotive scheduling problem, we introduce a novel decomposition approach. It exploits the fact that the locomotive master problem is empirically much easier to solve than the driver scheduling, which we treat as a subproblem. For any fixed solution of the master problem, we can use the subproblem to either confirm feasibility or to derive valid inequalities from various constraint classes to cut the infeasible master solution off and reiterate. To further improve solution times, we also develop a presolve heuristic. We conclude with a demonstration of the potential of our method by solving a real-world problem instance provided by DB Cargo Polska S.A.

3 - Partial dominance in branch-price-and-cut for the electric vehicle routing problem with time window

Stefan Faldum, Stefan Irnich, Timo Gschwind

The electric vehicle routing problem with time windows (EVRPTW) considers a fleet of battery-electric commercial vehicles (ECVs) that have a limited battery capacity and the possibility to recharge by visiting a recharging station. We focus on the EVRPTW variant that allows an ECV to visit multiple recharging stations and to recharge partially. When solving the problem with a column generation-based algorithm, the latter aspect leads to an interesting subproblem, i.e., a shortest-path problem with resource constraints and a (linear) tradeoff between the battery state and time. Longer recharging extends the driving range, while it may prohibit the timely arrival at a later customer due to his/her service time window. In this talk, we focus on the solution of the shortest-path subproblem with the help of a labeling algorithm that introduces a many-to-one dominance instead of the classical one-to-one dominance. We refer to this acceleration strategy as partial dominance. Extensive computational studies compare branch-price-and-cut algorithms equipped with partial dominance against traditional ones.

4 - Partial Dominance in Branch-Price-and-Cut for the Multi-Compartment Vehicle Routing Problem

Katrin Heßler, Stefan Irnich

This paper considers a multi-compartment vehicle routing problem with fixed compartment sizes. There are no incompatibilities between items and/or compartments, i.e. the packing is only constrained by the compartment sizes. The objective is to minimize the total distance of all vehicle routes such that all customer demands are met. We present branch-price-and-cut algorithms to solve this problem exactly. The pricing problem is formulated as a shortest path problem with resource constraints. We introduce a new labeling algorithm utilizing partial dominance in which certain extensions of one label may be dominated by the corresponding extensions of another label. Extensive computational tests show the advantage of using partial dominance over classical dominance.

■ FA-10

Friday, 9:00-10:20 - Schreckhorn

Facility location & picking & cutting

Stream: Logistics and Freight Transportation
Invited session
Chair: *Marc Gennat*

1 - Mobile service facilities with customer choice (MSFCC)

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 using out-of-the-box NLP solvers to solve already medium-sized instances. 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 approach.

2 - Solving the Skiving Stock Problem using Stabilized Column Generation and the Reflect Arcflow Model

Laura Korbacher, Stefan Irnich, John Martinovic, Nico Strasdat

The skiving stock problem consists of finding a maximum number of one-dimensional objects with a minimum threshold length recomposed from a given supply of short items of different lengths. We present a new exact multi-level approach that combines stabilized column generation and a pseudo-polynomial flow-based formulation, the so called reflect arcflow model. We exploit the observation that high-quality and even optimal solutions can be obtained from a reduced arcflow graph. We build such reduced graph with patterns from a column-generation approach that solves the linear relaxation of the Gilmore-Gomory-type of pattern-based model. The column-generation process is stabilized with dual optimal inequalities. Optimal solution are found in most cases without the consideration of the complete integer reflect arcflow model. Preliminary computational tests show that the proposed approach achieves convincing results on skiving stock instances of all common benchmark sets. For some very large-scale instances, several new proven optimal solutions have been found.

3 - Integrative zoning and item-to-zone assignment in pick-and-pass order picking systems - a basic decision model

Regina Thelen, Ralf Gössinger

Order picking is the logistic warehouse process of consolidating stored items according to customer orders. Since it is one of the most cost- and labor-intensive operations, the management of these activities is an important driver of warehouse performance. Pick-and-pass systems are zoned systems in which each picker only works at one zone and each zone only comprises a sub-set of items. Hence, order-related containers are routed along a sequence of zones to be filled up with the items needed for order fulfillment. When designing a pick-and-pass system two organizational problems need to be solved. How should the zones be formed and which item should be assigned to which zone? Usually, these problems are tackled in such a way that assignment is done after the zones were formed (sequential approach). This allows for fast solutions, but does not guarantee optimal solutions as soon as both problems are strongly interrelated. For minimizing the makespan of a pick-and-pass system, two time components are relevant: the time it takes to forward a container between zones, and the time it takes in a zone to put the required items in the container. Since both decisions unfold different impact on both time components, these problems are interrelated. However, general statements about the strength of interdependency are not available. In the intended paper, we propose a decision model that simultaneously decides on zone sizes and item-to-zone assignment in a makespan minimizing way. In order to identify drivers of interdependency, we conduct a numerical study in which the proposed model is compared to a sequential approach. Therefore, factors are varied that are hypothesized to have an impact on the strength of interdependence between the two decision problems.

4 - Tour Planning for Municipal Waste Collection Points Using Voronoi, Delaunay and TSP Strategies

Marc Gennat

In the investigated city 199 collection points for waste paper and glass bottles have to be cleaned from once a week up to six times a week. In all, 429 cleaning jobs per week have to be performed. These requirements and cleaning intervals are determined by the municipal waste disposal company. With given constraints the shortest sum of all routes from Monday to Saturday has to be computed. Some collection points are cleaned daily and others are cleaned up to six times a week. In this example collection points with four cleanings per week or less provide some degrees of freedom, which could be used to minimize the cost function. The last given constraint is determined by daily working hours, which is computed by cleaning time plus time of travel.

In this contribution a heuristic will be shown, which computes a local minimum. The TSP cost matrix is computed by using Google Maps Distance Matrix-API, thus, all 39,800 travel time durations are known and will take into account average travel speed with the expected average delays. Unfortunately, the travel time duration matrix does not correspond with a Euclidean geometry.

Using Voronoi diagrams and Delaunay triangulation, the collection points with the above mentioned degree of freedom can be assigned to the nearest route on a specific weekday. Hereby Euclidean geometry is used, which could result in assigning the wrong collection point to a route. With this, it is assumed, the computed result represents in general a sub-optimal solution. To gain the optimum all possible collection points could be assigned, which results in solving 13 billion TSPs.

Nevertheless, the initial route of the municipal company is improved by 29 percent using the presented algorithm.

■ FA-11

Friday, 9:00-10:20 - Wildstrubel

Assembly Lines and Repair Kit Problems

Stream: Supply Chain and Production Management
Invited session
Chair: *Christian Weckenborg*

1 - Branch-and-bound for the balancing of paced assembly lines under random sequences

Celso Gustavo Stall Sikora

Assembly lines in the automotive industry must comply with an enormous number of combinations of products that can be ordered. The different models of a family of cars are often produced in a single line, which must be flexible enough to cope with such a variety. In paced assembly lines, a station length longer than the cycle time equivalent brings the possibility of compensating heavier models with subsequent lighter models. Furthermore, utility work can be used to compensate for deviations in the processing time. This utility work is performed by skilled workers that work as floaters along the line. The cost minimization of an assembly line depends on the length delegated to the line and the amount of utility work used.

In this work, the optimization of the assignment of tasks to stations under a random sequence of products is explored. The stochasticity is modeled by probabilities of multiple options of each task which can be ordered for each product. A branch-and-bound algorithm is proposed to find the minimal cost of assignments with respect to line-length cost and expected utility work. For each given assignment and station length, a Markov Chain is used to determine the expected utility work.

2 - Anticipating technical car sequencing rules in the master production scheduling of mixed-model assembly lines

Thorben Krüger, Achim Koberstein

We propose a new linear programming based approach, which enables the consideration of technical car sequencing rules in the master production scheduling of mixed-model assembly lines at a much higher level of detail than previous approaches. To this end, we investigate certain interdependencies of car sequencing rules, which have largely been neglected so far, both in practice and in the research literature. We illustrate the existence and the impact of these interdependencies and show, that they induce additional implicit constraints, which can be represented by linear inequalities and incorporated into linear optimization models for master production scheduling. In a numerical study, we evaluate the approach and show for cases of up to six equipment options, that it can greatly reduce sequencing violations compared to existing approaches.

3 - The repair kit problem with fixed delivery costs

Christoph Rippe

Many manufacturers of heavy and bulky appliances offer on-site repair services for their products. These repair jobs are typically performed by service technicians who visit several customers per day with a set of spare parts called repair kit. The problem of managing the inventory of the spare parts carried by the technician is referred to as the repair kit problem. While fixed replenishment costs can make up an important share of the total costs associated with field repairs most contributions on the repair kit problem do not treat the replenishment frequency as a decision variable. We present a problem formulation that considers two types of fixed costs, fixed order costs per item ordered as well as fixed delivery costs for each shipment from the supplier to the technician. Our goal is to minimize the sum of both types of fixed costs and inventory holding costs subject to a job-fill-rate constraint. To manage the content of the repair kit we suggest individual (R,s,S)-policies for each spare part with common Rs for all parts sourced from the same supplier. That means the inventory position of a part is reviewed every R periods and raised up to the order-up-to level S when it is found to be smaller or equal to the reorder level s. We derive a closed-form expression for the job-fill-rate and suggest a heuristic to determine the length of the review period(s) as well as the reorder and order-up-to-levels for spare parts carried in the repair kit. A numerical experiment is used to demonstrate the impact of the replenishment frequency on the total costs incurred.

4 - Disassembly Line Balancing with Collaborative Robots

Christian Weckenborg

Against the background of scarce natural resources, the recovery of components and materials from discarded products is increasingly relevant. The disassembly of products, however, must be profitable for the involved actors. Therefore, disassembly is frequently conducted efficiently using disassembly lines. The balancing of such disassembly lines and decisions on the disassembly depth of the affected products are simultaneously considered to maximize profitability. Today, partial disassembly dominates this industry. While this is economically advantageous, a high ecological potential may remain unused. In recent years, collaborative robots can support workers in the manual disassembly of products to further enhance the disassembly processes' efficiency and profitability. However, the increase in efficiency due to the partial automation of disassembly tasks may also result in a higher realized disassembly depth and thus account for ecological advantages. In our contribution, we investigate this effect for an illustrative example using a model-based approach.

■ FA-12

Friday, 9:00-10:20 - Faulhorn

Electric Mobility

Stream: Mobility and Traffic
Invited session
Chair: *David Rößler*

1 - Optimizing the Technology Split for a Decarbonized Bus Network
Ulrich Pferschy, Frieß Nathalie

Many cities are pursuing strategies to replace their Diesel-powered municipal bus fleet by (locally) emission-free vehicles. Nowadays many demonstration cases are operating single lines with one particular technology. However, we are considering a full fleet conversion which can be based on a mix of different technologies. The optimal choice requires an in-depth assessment of local operating conditions and is accompanied by a number of complex, interrelated strategic and operational decisions. The goal of this work is to identify an optimal composition of technologies, namely a cost-optimal mix of hydrogen-powered fuel cell buses, overnight charging buses with longer range and opportunity charging buses. The latter technology requires regular short-term charging operations at charging stations, which have to be positioned at suitable bus stops throughout the bus network, mainly at end stops.

Depending on the number of buses for each technology, the corresponding loading and refueling infrastructure has to be set up. This incurs piecewise constant cost with several steps. To decide on the suitable number of buses and charging stations, also line schedules, vehicle rotation and charging schedules have to be taken into account. We set up a fairly complicated ILP-model for the minimization of the total cost of ownership. For real-world data of the city of Graz (34 bus lines, 480km total route length) we reach optimal solutions within reasonable computation time. The developed model can serve as a decision tool to evaluate the effect of changes in cost components and other parameters (such as vehicle specifications, battery capacities, charging power levels, etc.) as the available technologies keep evolving.

2 - Planning robust charging infrastructure for battery electric bus systems
Miriam Stumpe, David Rößler, Natalia Kliewer, Guido Schryen

Given the global efforts to reduce emissions, one of the biggest challenges currently facing public transport is the transition from traditional fuel-based bus transportation towards electric bus systems. Hence, public transport operators are under growing pressure not only to replace their diesel buses with electric buses, but also to provide a supporting charging infrastructure. The uncertainty about the development of technological and economic factors poses a hazard to the feasibility and cost efficiency of the electric bus system. As a result, it is necessary to solve two intertwined planning problems - the long-term charging location planning and the operational electric vehicle scheduling - in order to determine a robust charging infrastructure, which remains feasible and sufficiently low-cost when environmental factors vary. Several approaches in the literature account for uncertainty due to changes of environmental factors by applying sensitivity analysis. However, most of these focus on variations in only a few factors or assume fixed vehicle schedules. We contribute to closing this research gap by (1) simultaneously optimizing the charging infrastructure and vehicle schedules and (2) improving the robustness of the resulting charging infrastructure. In the presented approach, we draw from an existing implementation of a Variable Neighborhood Search (VNS) from prior work. The VNS is executed repeatedly with varying factors and using the previous solution as its starting point, thus leveraging previously gained knowledge through cascading effects. We describe a series of computational experiments on several real-world instances of different size and composition to show that for each bus network a kernel set of charging locations can be identified.

3 - Electric Bus Scheduling in Public Transportation
Fabian Löbel, Ralf Borndörfer, Steffen Weider

Out of environmental and health concerns, interest in electric vehicles has grown rapidly over the last decade, especially in the public transportation sector. The short driving range and long recharge downtime of battery electric buses render established vehicle scheduling procedures inadequate and solving the electric bus scheduling problem in a satisfactory manner is an ongoing area of research. With this contribution we wish to assess the problem, propose solution angles and provide some computational results.

4 - Electric Vehicle Scheduling and Charging Scheduling To Increase Renewable Energy Utilization in the Public Transport Sector
David Rößler, Paolo Graniero, Natalia Kliewer

Bus transport systems are a fundamental component of the public transport sector in many urban and suburban areas. Their electrification is one important step in the green transition of the transport sector. However, due to range limitations, the integration of battery-electric buses in the transport system poses several challenges. Public transport operators need to schedule not only the bus trips, but also the charging of the buses' batteries. Meanwhile, the charging process itself requires careful consideration: uncontrolled charging of the typically large batteries might overload the local grid, causing grid disturbances or requiring an early replacement of grid components. Additionally, the environmental benefits of electric buses might be dramatically reduced, if the energy used to charge their batteries is not generated by renewable sources. The fluctuation of the energy yield of e.g. photovoltaic arrays makes it necessary to consider the resulting uncertainty when scheduling charging processes. Maximizing the amount of self-produced energy for charging process is crucial in obtaining a cost-efficient and truly green operation of the transport system. Hence, the conjoint consideration of e-mobility and the energy system is key to increasing sustainability in the transport sector. In this work, we propose an integrated vehicle and charging scheduling approach that considers the interaction between the bus fleet, the power grid, and a local photovoltaic power system. We use a metaheuristic algorithm for the electric vehicle scheduling problem from prior work and extend it to consider the uncertainties in photovoltaic energy generation. The results are then analyzed regarding the robustness of resulting schedules against renewable energy yield fluctuations.

■ FA-13

Friday, 9:00-10:20 - Blüemlisalp

Flows and Markets

Stream: Game Theory and Behavioral Management
Invited session
Chair: *Till Heller*

1 - A pricing scheme for convex mixed-integer nonlinear competitive equilibrium problems that minimises side-payments
Lukas Hümbs, Alexander Martin, Lars Schewe

Competitive equilibria exist in convex markets, however, in the presence of integralities this is generally not the case. Various pricing schemes have been developed that compute prices and side-payments which support an equilibrium. We present a pricing scheme that leads to a welfare optimal solution for convex mixed-integer nonlinear problems via a uniform linear price for the traded good and discrimi- natory side-payments. This pricing scheme is based on the well-known IP-pricing scheme and returns revenue adequate prices that are easy to interpret. The main goal of the scheme is to keep the side-payments as low as possible.

2 - On the Existence of Energy Market Equilibria with Convex and Nonconvex Players
Julia Grübel, Olivier Huber, Lukas Hümbs, Max Klimm, Martin Schmidt, Alexandra Schwartz

Motivated by examples from the energy sector, we consider a special type of market equilibrium problems (MEPs) involving players both with convex and nonconvex strategy spaces or objective functions. Such problems naturally occur in settings, where equilibrium problems for energy trading are combined with aspects of the actual energy transport through networks. We propose an algorithm that decides on the existence of equilibria of MEPs of this type and that computes a market equilibrium in case of existence. Moreover, we provide both a uniqueness and a non-existence result for MEPs that include players with unique best responses. Finally, we test the proposed algorithm on well-known energy market instances from the power and gas literature. There, nonconvexities mainly arise from considering the transmission system operator as an additional player who, e.g., switches lines or faces nonlinear physical laws. Our numerical results indicate that an equilibrium often exists, especially for the case of continuous nonlinearities in the context of gas market problems.

3 - Approximate Parametric Computation of Minimum Cost Flows with Convex Cost
Philipp Warode, Max Klimm

Given a graph, node balances, and flow dependent edge cost functions, a flow that minimizes the sum of all edge cost with respect to the flow is called a minimum cost flow. The computation of minimum cost flows is a central problem in the realm of combinatorial optimization and is well-studied. We consider a parametric variant of the problem, where the node balances (i.e., the in- and outflow rates at the nodes) are parametrized by a one-dimensional parameter. A solution to this parametric problem is a function that maps a parameter value to a minimum cost flow for the respective node balances. In this work, we analyze this minimum cost flow function and investigate properties such as continuity and differentiability. Further, we use the insights from the analysis in order to derive a practical algorithm that computes the minimum cost flow function approximatively for a given network and arbitrary convex cost. Finally, we test an implementation of the algorithm on real-world traffic and gas network instances and find that the algorithm is applicable in practice.

4 - Computing the egalitarian allocation with network flows
Till Heller, Sven Krumke

In a combinatorial exchange setting, participants place sell (resp. buy) bids on combinations of traded goods. Besides the question of finding an optimal selection of winning bids, the question of how to share the obtained profit is of high importance. The egalitarian allocation is a well-known solution concept of profit sharing games which tries to distribute profit among participants in a most equal way while respecting individual contributions to the obtained profit. Given a set of winning bids, we construct a special network graph and show that every flow in said graph corresponds to a core payment. Furthermore, we show that the egalitarian allocation can be characterized as an almost equal maximum flow which is a maximum flow with the additional property that the difference of the flow values on given edge sets is bounded by a constant. With this, we are able to compute the egalitarian allocation in polynomial time.

■ FA-14
Friday, 9:00-10:20 - Wetterhorn

MCA and LCA

Stream: Decision Analysis and Support
Invited session
Chair: *Alice H. Aubert*

1 - Multi-criteria portfolio construction based on PROMETHEE ranking for environmental decision-making
Erik Pohl, Jutta Geldermann

Environmental decisions are often complex and need to consider various conflicting criteria. PROMETHEE is an outranking method to treat multi-criteria problems with a discrete set of available alternatives that has been widely applied in environmental decision-making. In order to find a preferred alternative, PROMETHEE I and II can be used to determine a partial or complete ranking based on the decision makers (DMs) preference. Some real-world decisions however require determining a set or portfolio of alternatives regarding goals and constraints given by the DM, e.g., find a subset of good alternatives maximizing the PROMETHEE net flow under different constraints considering dependencies among alternatives. We present a linear optimization model to determine a portfolio of alternatives based on their PROMETHEE ranking. While defining the portfolio, we consider various constraints and interdependencies. We illustrate this approach with a case study on energy saving and emission reduction measures in a container terminal. A Life Cycle Assessment (LCA) is used to measure and compare the environmental impact. We furthermore discuss, how to explicitly include the DMs preferences during the portfolio construction. Within the case study, a roadmap towards a more profitable and ecological port operation can be developed by our approach.

2 - Prospective multi-criteria analysis in the water-energy nexus
Sebastian Schär, Jutta Geldermann

Water and energy systems are interrelated since energy is needed to treat, distribute and discharge water and wastewater. But also for fulfilling energy demands, water is required in large quantities, e.g. for fuel supply, plant operations or hydropower plants. Therefore, both sectors as well as their dynamic interactions should be considered together in many long-term decisions. The water-energy nexus is not only subject to uncertainties regarding forecasts of resource demands and availabilities, but also regarding the assessment of future impacts and consequences of the actual decision. Multi-criteria analysis methods combined with problem structuring methods, e.g. scenario planning, offer the possibility to account for such uncertainties in the assessment of planning options. We present a framework based on qualitative system dynamics for capturing various kinds of uncertainties and the outranking method PROMETHEE for strategic decision-making in the water-energy nexus. This way, interrelationships and path dependencies in the water-energy nexus can be assessed. System dynamics is applied to reveal interdependencies between criteria and to identify criteria subject to reinforcing feedback loops. A case study for the evaluation of alternatives in Integrated Water Resources Management (IWRM) in the Middle East illustrates how the methodological integration of system dynamics into the outranking method PROMETHEE enables a prospective assessment of technical solutions in strategic decisions.

3 - Determining and resolving conflicts in the configuration of high-performance pumps
Sebastian Velten, Christopher Paul Hamkins, Tobias Fischer, Pascal Wortel

Modern high-performance pumps are complex systems that are used in a wide range of different applications, such as drinking water supply or wastewater disposal. In order to structure the adaptation possibilities of a pump series, a set of features is defined. Different values can be assigned to these features and they can thus be used to describe the characteristics of a specific pump.

The feature combinations that are technically possible are specified in restriction tables. These tables each include a subset of the features as columns and contain one row for each acceptable combination. Since typically between 500-1000 of these tables are given and some further constraints must also be taken into account, determining a valid configuration is not an easy task.

A greater challenge, however, is the analysis of infeasibilities. These can arise in particular when a combination of features requested by a user is not compatible with the restriction tables and the other constraints. In this case, the user is interested in possible solutions that meet as many of his original requirements as possible. Moreover, it may already happen during the definition of the restriction tables that conflicting tables have to be identified.

In the talk, we first introduce a Constraint Programming model for the configuration problem. After that the main focus lies on the presentation of an algorithm for determining all minimal conflicts in case the configuration problem (possibly extended by user decisions) is infeasible. In addition, an approach for finding resolutions by relaxing hitting sets of the set of minimal conflicts is discussed. The talk ends with computational results showing the efficiency and applicability of the proposed approach in practice.

4 - Supporting citizen participation in decision-making: Can gamified interventions and serious games help?
Alice H. Aubert, Judit Lienert

Gamification and serious games (GSG) are increasingly used in participatory environmental modelling for policy-making. For instance, role-playing simulation games are now rather common. Interest in GSG as participatory tools in complex multi-objective multi-stakeholder decision processes is jut emerging. ,. GSG should increase motivation, engagement, and factual, normative and social learning of participants. The benefits of GSG are yet to be backed with systematic assessment. After motivating citizen participation in OR processes, we will shortly review the existing diversity of GSG for decision- and policy-making. We will reflect on how each phase of the decision process could benefit from GSG and how GSG could potentially address the shortcomings observed in citizen participation in OR. Thereafter, we will focus on our recent projects targeting two phases of a multi-criteria decision analysis (MCDA) process: (1) generating diverse objectives in the problem-structuring phase, and (2) eliciting weights in the preference elicitation phase. GSG are applied to a wastewater management decision, but the concept of GSG could easily be applied to other topics. Importantly, we will present procedures to systematically assess GSG, and draw conclusions for our GSG applications. We invite fellow researchers to apply and further improve both GSG in diverse applications and the assessment procedure we developed to fully understand the added benefits of GSG in supporting citizen participation in decision-making.

■ FA-15

Friday, 9:00-10:20 - Silberhorn

New models and approaches in scheduling

Stream: Project Management and Scheduling
Invited session
Chair: *Robert Klein*

1 - Data-driven generation of digital twin models for predictive-reactive job shop scheduling

Felix Grumbach, Pascal Reusch

Job Shop Scheduling Problems (JSP) are becoming more extensive to depict real planning situations. A current research trend is, to interlink the physical environment with a digital twin to carry out realistic analytics. It can be assumed, that simulation-based optimization will gain practical importance in context of predictive and reactive scheduling. It is fueled by the fact, that AI research has achieved great success in recent years. E.g., reinforcement learning agents (RLA) can explore environments in a self-learning manner without an explicit implementation.

However, it is a complex matter to develop a digital twin that maps the shopfloor specifics properly. A key challenge is to reduce the complexity of the underlying real-world situation to its essential components. Our current research is focussed on complex dual resource JSP in socio-technical manufacturing companies. We mapped the identified parameters and dependencies into a relational object model (OM). First, the OM represents a live interface to the production environment (enables reactive scheduling). Second, the OM is used to generate a concrete simulation environment via a generic routine. Third, the OM contents can be used for forecasting purposes (enables predictive scheduling).

We have found that it is effective to integrate even complex scenarios in this way. We have developed a generic, easily expandable and adaptable basic framework for a problem-oriented simulation, which can be initialized with live operational data. Based on current literature and case studies we explain the defined workflow. In detail we will describe the OM and the generic simulation routine including a constraint module. It is followed by an outlook on how RLA can be implemented on identified decision nodes.

2 - Modelling challenges in airline crew scheduling

Emily Curry, Henrik Wallenius

The airline crew scheduling problem is a large scale optimization problem where individual work tasks (trips) are assigned on crew's rosters in an optimal way. Solving this problem allows an airline to distribute the workload in an efficient way while at the same time publish stable rosters with high quality to their crew population. The Jeppesen Crew Rostering Optimizer is able to solve some of the world's largest crew scheduling problems, and is used by airlines all over the world.

Solving this problem is a big challenge not only because of its size, but also because each airline has their unique set of rules and solution preferences that need to be accommodated by the optimizer. A sub problem to the airline crew scheduling problem is to generate good roster candidates for each crew that could potentially be part of an optimal solution to the global problem. One way to achieve this is to setup a network of trips for each crew and solve a shortest path problem to obtain the best roster. The structure of the network captures some properties of the problem. However, there are many complicating factors such as satisfying a large number of complex rules, non-additive cost functions and re-adapting to an ever changing reality that must be handled by each individual scheduling problem. By making a more advanced and easily customized model it is possible to handle these problems but it comes at a cost.

In this presentation we will address some of the challenges with the roster generation and reflect on the trade-off between performance and quality.

3 - A new IP formulation for the single picker routing problem with scattered storage

Stefan Irnich

The basic single picker routing problem (SPRP) assumes that a set of picking positions in the warehouse is given. The task is to find a minimum length picking tour that starts and ends at the given I/O point and traverses all positions (at least once). For a standard rectangular single-block warehouse, the dynamic-programming approach of Ratliff and Rosenthal (1983) can be applied. When one or several SKUs are pickable from more than one picking position, the warehouse is operated as a scattered storage warehouse a.k.a. mixed shelves warehouse. Recent works stress that scattered storage is predominant in modern e-commerce warehouses of companies like Amazon or Zalando. The only know solution approaches for the NP-hard SPRP with scattered storage are MIP-based. We present a new IP formulation for the SPRP with scattered storage that can be generalized to different warehouse layouts, the multi-IO point case, and profitable picker-routing problems.

4 - Dynamic Order Acceptance and Scheduling Approaches for Two Machines Flow Shop Scheduling Problems

Sebastian Spindler, Claudius Steinhardt, Robert Klein

We consider a dynamic order acceptance problem where accepted requests for jobs need to be scheduled in a two machines flow shop. In contrast to the order acceptance and scheduling literature, we assume that the request for a job needs to be accepted or rejected at the moment where the request arrives. In a subsequent production phase, all jobs need to be scheduled in a two machines flow shop. We formulate the problem with a stochastic dynamic programming formulation and develop different approaches that yield decision support for accepting or rejecting an incoming request without the knowledge about future requests based on the approximation of opportunity costs. In an extensive numerical study, we finally compare the anticipative and non-anticipative approaches to benchmark approaches from the literature.

■ FA-16

Friday, 9:00-10:20 - Schilthorn

Simulation/Machine Learning in Health Care

Stream: Health Care Management
Invited session
Chair: *Michael Römer*

1 - The Value of Data Collection: Validation of a Simulation Model for Emergency Medical Services

Sven Watzinger, David Olave-Rojas, Stefan Nickel

Emergency Medical Services (EMS) are complex logistical systems with multiple stochastic elements. This makes ressource planning a difficult task on the strategic, tactical as well as operational level. In recent years, the efforts to deal with this complexity by gathering and utilizing real-world data have increased significantly. Simulation is a suitable and commonly used tool to support the logistical planning in EMS due to its capability do integrate the dynamic and stochastic elements of EMS systems. This capability is especially useful when the simulation is coupled with analytical OR methods. Simulation by itself is not capable of delivering optimal solutions to problems such as location planning of ambulances. Analytical models can find optimal solutions, but oftentimes require a reduction in complexity from the real-world system, which inevitably leads to a loss of information. When combined, simulation can counterbalance this loss of information. The transferability of simulation results to real-world systems is highly dependent on the amount and quality of the data used to parameterize and validate the simulation model. In 2011, the department for quality assurance of emergency medical services was founded in the federal state of Baden-Wuerttemberg in Germany. The department collects data from EMS trips from the 35 EMS regions in the federal state covering around 11 Mio. inhabitants. The aim of our joint project with the department is to develop a simulation model based on the collected data and to use the simulation and analytical models to support the planning of resources in the EMS. In this talk we present preliminary results of the project and discuss the challenges and opportunities of the development of the simulation model.

2 - The Effects of a Boarding Area on Patient Waiting Time in the Emergency Department using a Discrete-Event Simulation

Jakob Heins

Growing patient volume combined with limited capacities in emergency departments represents a challenge for hospital management to maintain a high quality of work without an increase in waiting times. Often patients cannot be directly admitted to the hospital after treatment in the emergency department due to limited bed capacities on the intensive care units or regular ward stations. Various approaches to solving this problem have been proposed in recent years, including ideas for active bed management within the emergency department or different allocation rules for specific boarding areas. This study develops a discrete-event simulation approach to simulate the patient flow of an emergency department based on real data. Furthermore, the set up of different patient boarding area systems are compared in a scenario analysis with other mechanisms such as adding more treatment beds to evaluate the effects on patients length of stay and waiting times.

3 - Combining Machine Learning and Monte-Carlo Simulation to Support Intensive Care Occupancy Management

Arne Henning Witteborg, Michael Römer, Rainer Borgstedt, Gerrit Jansen

Intensive medical care units (ICUs) are one the most complex, sensitive and financially important resources of a hospital. Controlling the utilization of the available ICU beds, however, is a challenging endeavour, since the ICU occupancy is affected by highly uncertain factors such as emergency patients and variations in length of stay. To support a risk-oriented management of ICU occupancy, we propose a Monte Carlo-Simulation approach that provides probabilistic estimates of the ICU occupancy for the next couple of days. The distributions of the input factors are learned from historical data. In particular, we employ a probabilistic Machine Learning approach that uses standard physiology and intervention scores to obtain a probability distribution for the length of the remaining stay for each ICU patient. The results of the simulation are used in a system that is designed to support decisions related the scheduling of ICU-relevant elective surgeries by providing a traffic-light style visualization of the risk of reaching capacity limits. We evaluate our approach with historical data from a German hospital showing that some occupancy peaks could have been avoided by postponing elective surgeries scheduled in situations with a high risk of hitting capacity limits.

4 - Artificial intelligence-based decision support in laboratory diagnostics

Alexander Scherrer, Michael Helmling, Christian Singer, Sinan Riedel, Karl-Heinz Kuefer

Many diseases like SARS-CoV-2 infections at early stage cause characteristic value changes in blood counts. Modern laboratory medicine thus allows for an efficient screening and preliminary diagnosis. The workflows of lab medicine, however, feature a high-throughput and widely manual processing of blood counts. The resulting capacity bottlenecks and risks of human failure limit the efficient and reliable large-scale processing of blood counts. The COVID-19 pandemic has also indicated need for method and technological advances in lab medicine. This research work introduces a modern solution approach for lab diagnostics based on AI and decision support. Blood counts from laboratory information systems first undergo a data cleansing and extraction of the crucial values. The preprocessed data then enter an analysis with a decision tree-based classifier. This method approach uses the CART algorithm with adequate node split and pruning strategies in combination with a random forest algorithm with suitable feature selection. The classifier was trained on two medical data sets of different origin and characteristics. The data analysis produces for the blood counts preliminary diagnostic results annotated with values indicating their reliability. This property of decision tree methods of providing insight into the creation of results allows for a conceptual connection to decision making. The results of analysis are provided to lab physicians with basic decision support features for final medical judgement. An export routine allows for a transfer of results into the laboratory information system, thereby closing the loop to existing workflows. The whole approach of digitally assisted lab diagnostics is provided as a prototypic web service based on a pay-per-use business model.

Friday, 10:40-11:40

■ FB-01

Friday, 10:40-11:40 - Bundeshaus

SP talk Gansterer

Stream: PC Stream
Sponsored session
Chair: *Margaretha Gansterer*

1 - Collaborative vehicle routing: computational and game theoretical aspects
Margaretha Gansterer

The Sharing Economy is on the rise. Traditional business models have to be adapted and players have to learn how to survive in a world of shared idle capacities and digital platforms. The concept of shared transportation resources, also denoted as collaborative vehicle routing, is one of the hot topics in transportation and logistics. A collaboration can be described as a partnership between two or more companies to optimize operations by making joint decisions and sharing information, resources, or profits. While the willingness to enter coalitions does exist, the success of collaborations strongly depends on mutual trust and behavior of participants. Hence, proper mechanism designs, where carriers do not have incentives to deviate from jointly established rules, are needed. In this talk, we elaborate horizontal collaborations, where logistics providers share resources with their competitors through the exchange of selected transportation requests. The aim is to increase the overall efficiency of the transport industry, by avoiding costly and pollutive empty trips. We focus on decentralized exchange mechanisms, which are based on the assumption that no fully informed decision maker exists. In such mechanisms, efficient solution methods for complex routing problems have to be tackled, while game theoretical aspects have to be taken into account. The talk gives insights on auction-based systems, where several strongly related decision problems have to be integrated. We analyze, for instance, whether carriers face a Prisoner's Dilemma when selecting requests for trading. Recent findings as well as promising future research directions are presented.

■ FB-02

Friday, 10:40-11:40 - Zytglogge

SP talk Liers

Stream: PC Stream
Sponsored session
Chair: *Frauke Liers*

1 - Mixed-Integer Robust Optimization: Some Algorithms and Some Applications
Frauke Liers

Protecting optimization problems against uncertainties is an exciting research area where new methods and algorithms are developing rapidly. One way of protecting against uncertainties that occur in real-world applications is to determine best possible robust decisions that are feasible regardless of how uncertainties manifest themselves within predefined uncertainty sets. In this talk, we will review some of the recent developments in particular for mixed-integer robust optimization problems that often apply reformulation, decomposition as well as approximation approaches. Data-driven approaches are on the rise as well. (Mixed-integer) discrete decisions add another difficulty in algorithmic tractability, both in theory as well as in practice. We will also look into some robust energy network applications together with some overview of the literature. In electricty networks, we show that robust protection can also be used for a robust safe approximation of joint chance constrained in DC Optimal Power Flow problems. For the robust operation of gas networks, we review reformulation and decompotion approaches for the occurring mixed-integer two-stage nonconvex robust problems, where the latter use an outer approximation for a bundle method that is able to deal with nonconvexities.

■ FB-03

Friday, 10:40-11:40 - Münster

SP talk Wozabal

Stream: PC Stream
Sponsored session
Chair: *David Wozabal*

1 - Short-Term Power Markets: Towards Optimal Trading Decisions
David Wozabal

The talk explores optimal strategies for trading on short-term power markets. We take the perspective of a single firm that does not act strategically but treats market outcomes as exogenous and random. The problem is of high practical relevance for most players in the electricity sector and, correspondingly, there is an extensive literature on the subject. However, due to the high number of traded products and the increasing influence of variable intermittent production technologies which necessitates repeated rebalancing until shortly before delivery, the resulting decision problems are of considerable computationally complexity. In particular, finding optimal strategies for trading on continuous intraday markets remains a largely open problem as most authors consider only simplified versions of the market leading to policies that are not implementable in practice. We review the current state-of-the-art and discuss the specifics of different short-term markets and the resulting trade-offs associated with trading on them. We then go on to show that, for firms that operate on multiple markets, optimal policies for individual markets are interdependent and decisions therefore have to be coordinated. We demonstrate how stochastic optimization approaches can be combined with model predictive control to arrive at near optimal trading strategies on an hourly granularity and quantify the value of coordination between the day-ahead market and a continuous intraday market. To push the trading frequency to a sub-hourly level, we discuss a parametric weather-based trading heuristic based on intraday updates of renewable production forecasts. We evaluate the resulting decisions out-of-sample based on detailed order book level data.

Friday, 12:00-13:00

■ FC-01

Friday, 12:00-13:00 - Bundeshaus

EURO Plenary talk Dür

Stream: PC Stream
Sponsored session
Chair: *Mirjam Duer*

1 - Conic optimization: an application-oriented survey
Mirjam Duer

A conic optimization problem is a problem involving a constraint that the optimization variable be in some closed convex cone. Linear optimization is a prominent example, where the nonnegativity constraint can be interpreted as requiring that the variable should be in the cone of nonnegative vectors. Other examples are second order cone problems (SOCP) where the variable is constrained to be in the second order cone, and semidefinite programming (SDP) where the matrix variable is required to be in the cone of positive semidefinite matrices. More general cones appear in special applications. In this talk, we will highlight the enormous modeling power of conic optimization and review recent progres made in this field. While the past decades have seen research mainly in linear conic optimization, interest has now shifted to nonlinear and mixed-integer conic optimization. We will discuss algorithmic progress made in this direction as well as new fields of application. Special emphasis will be given to applications of conic optimization appearing in operations research.

STREAMS

Analytics

Philipp Baumann
University of Bern
philipp.baumann@pqm.unibe.ch

Jochen Gönsch
University of Duisburg-Essen
jochen.goensch@uni-due.de

Ralph Grothmann
Siemens AG
Ralph.Grothmann@siemens.com

Thomas Setzer
KIT
thsetzer@gmail.com

Track(s): 14

Decision Analysis and Support

Reinhard Bürgy
University of Fribourg
reinhard.buergy@unifr.ch

Jutta Geldermann
University of Duisburg-Essen
jutta.geldermann@uni-due.de

Track(s): 14

Discrete and Combinatorial Optimization, sponsored by FICO

Sophie Parragh
Johannes Kepler University Linz
sophie.parragh@jku.at

Ulrich Pferschy
University of Graz
pferschy@uni-graz.at

Bernard Ries
Université de Fribourg
bernard.ries@unifr.ch

Jens Schulz
FICO
jensschulz@fico.com

Track(s): 4 5 6 7

Energy and Environment

Russell McKenna
University of Aberdeen
russell.mckenna@abdn.ac.uk

Dominik Möst
Technische Universität Dresden
Dominik.Moest@tu-dresden.de

Steffen Rebennack
Karlsruhe Institute of Technology (KIT)
steffen.rebennack@kit.edu

Track(s): 8 9

Finance

Michael H. Breitner
Institut für Wirtschaftsinformatik
breitner@iwi.uni-hannover.de

Andrea Gaunersdorfer
University of Vienna
andrea.gaunersdorfer@univie.ac.at

Elmar Lukas
Otto-von-Guericke-University of Magdeburg
elmar.lukas@ovgu.de

Track(s): 11

Game Theory and Behavioral Management

Michael Becker-Peth
Rotterdam School of Management, Erasmus University
m.beckerpeth@rsm.nl

Max Klimm
Technische Universität Berlin
klimm@math.tu-berlin.de

Track(s): 13

Health Care Management

Patrick Hirsch
University of Natural Resources and Life Sciences, Vienna
patrick.hirsch@boku.ac.at

Marion Rauner
University of Vienna
marion.rauner@univie.ac.at

Katja Schimmelpfeng
University of Hohenheim
katja.schimmelpfeng@uni-hohenheim.de

Track(s): 16

Heuristics, Metaheuristics and Matheuristics

Karl Doerner
University of Vienna
karl.doerner@univie.ac.at

Paul Kaufmann
Mainz University
paul.kaufmann@uni-mainz.de

Roberto Montemanni
University of Modena and Reggio Emilia
roberto.montemanni@unimore.it

Matteo Salani
Idsia - Usi/supsi
matteo.salani@idsia.ch

Track(s): 7

Logistics and Freight Transportation

Margaretha Gansterer
University of Klagenfurt
margaretha.gansterer@univie.ac.at

Stefan Irnich
Johannes Gutenberg University Mainz
irnich@uni-mainz.de

Sven Müller
Otto-von-Guericke-University Magdeburg
sven.mueller@ovgu.de

Michael Schneider
RWTH Aachen
schneider@dpo.rwth-aachen.de

Track(s): 9 10

Mobility and Traffic

Jan Fabian Ehmke
University of Vienna
jan.ehmke@univie.ac.at

Natalia Kliewer
Freie Universitaet Berlin
natalia.kliewer@fu-berlin.de

Virginie Lurkin
TU Eindhoven
v.j.c.lurkin@tue.nl

Track(s): 7 12

OR in Engineering

Andreas Klinkert
Zurich University of Applied Sciences (ZHAW)
klnk@zhaw.ch

Ulf Lorenz
Universitaet Siegen
ulf.lorenz@uni-siegen.de

Track(s): 16

PC Stream

Nina Ackermann
Universitaet Bern
nina.ackermann@pqm.unibe.ch

Norbert Trautmann
University of Bern
norbert.trautmann@pqm.unibe.ch

Track(s): 1 2 3 15

Project Management and Scheduling

Dirk Briskorn
University of Wuppertal
briskorn@uni-wuppertal.de

Hans Kellerer
University of Graz
hans.kellerer@uni-graz.at

Norbert Trautmann
University of Bern
norbert.trautmann@pqm.unibe.ch

Track(s): 15

Revenue Management

Christiane Barz
University of Zurich
christiane.barz@business.uzh.ch

Robert Klein
University of Augsburg
robert.klein@wiwi.uni-augsburg.de

Claudius Steinhardt
Bundeswehr University Munich (UniBw)
claudius.steinhardt@unibw.de

Track(s): 13

Supply Chain and Production Management

Olivier Gallay
University of Lausanne
olivier.gallay@unil.ch

Martin Grunow
Technische Universität München
martin.grunow@tum.de

Tina Wakolbinger
WU (Vienna University of Economics and Business)
tina.wakolbinger@wu.ac.at

Track(s): 7 11

Systems Modeling and Simulation

Klaus Altendorfer
FH Oberösterreich
klaus.altendorfer@fh-steyr.at

Maximilian Moll
Universität der Bundeswehr München
maximilian.moll@unibw.de

Andrea Emilio Rizzoli
Scuola universitaria professionale della Svizzera italiana (SUPSI)
andrea.rizzoli@supsi.ch

Christian Stummer
Bielefeld University
christian.stummer@uni-bielefeld.de

Track(s): 9

Session Chair Index

till.heller@itwm.fraunhofer.de
Optimization, Fraunhofer ITWM, Germany

Heßler, Katrin FA-09
khessler@uni-mainz.de
Chair of Logistics Management, Gutenberg School of Management and Economics, Johannes Gutenberg University Mainz, Mainz, Germany

Hirsch, Patrick TA-16
patrick.hirsch@boku.ac.at
Institute of Production and Logistics, University of Natural Resources and Life Sciences, Vienna, Wien, Austria

Hobbie, Hannes TD-08, WC-08
hannes.hobbie@tu-dresden.de
Chair of Energy Economics, TU Dresden, Dresden, Germany

Hochstättler, Winfried TA-04
winfried.hochstaettler@fernuni-hagen.de
FU Hagen, Hagen, Germany

Johnsen, Lennart TA-12
lennart.johnsen@bwl.uni-kiel.de
Universität Kiel, Germany

Kaiser, Florian TB-14
florian-klaus.kaiser@kit.edu
Karlsruhe Institute of Technology, Germany

Kimms, Alf WD-01
alf.kimms@uni-due.de
Mercator School of Management, University of Duisburg-Essen, Campus Duisburg, Duisburg, Germany

Klamroth, Kathrin TB-05
klamroth@math.uni-wuppertal.de
Department of Mathematics and Informatics, University of Wuppertal, Wuppertal, Germany

Klein, Robert WB-13, FA-15
robert.klein@wiwi.uni-augsburg.de
Chair of Analytics & Optimization, University of Augsburg, Augsburg, Germany

Kuhlmann, Renke TD-05, WC-05, FA-06, WE-06
rkuhlmann@gams.com
GAMS Software GmbH, Germany

Kuhn, Daniel TC-02
daniel.kuhn@epfl.ch
EPFL, Switzerland

Kupfer, Stefan TB-11
stefan.kupfer@ovgu.de
Faculty of Economics and Management, LS Financial Management and Innovation Finance, Otto-von-Guericke-University of Magdeburg, Magdeburg, Germany

Kämpf, Nicki Lena WE-12
NickiLena.Kaempf@beuth-hochschule.de
Beuth Hochschule Berlin, Berlin, Berlin, Germany

Lange, Julia WE-15
julia.lange@wiwi.uni-kl.de
Chair of Logistics, University of Kaiserslautern, Kaiserslautern, Rheinland-Pfalz, Germany

Lendl, Stefan WC-04
lendl@math.tugraz.at
Institute of Operations und Information Systems, University of Graz, Graz, Austria

Letmathe, Peter WB-15, WC-15
Peter.Letmathe@rwth-aachen.de
Faculty of Business and Economics, RWTH Aachen University, Aachen, Germany

Leuthold, Fabian WE-14
fabian.leuthold@ost.ch
Institute for Modelling and Simulation, OST - Eastern Switzerland University of Applied Sciences, OST - Ostschweizer Fachhochschule, St. Gallen, St. Gallen, Switzerland

Liepold, Christina WC-11
christina.liepold@tum.de
TUM School of Management, Technical University of Munich, München, Bavaria, Germany

Liers, Frauke FB-02
frauke.liers@math.uni-erlangen.de
Department Mathematik, FAU Erlangen-Nuremberg, Erlangen, Germany

Locatelli, Alberto TB-07
alberto.locatelli@unimore.it
Department of Sciences and Methods for Engineering, University of Modena and Reggio Emilia, Travesio, PN, Italy

Luangpaiboon, Pongchanun TD-07
lpongch@engr.tu.ac.th
Industrial Engineering, Thammasat University, Pathumthani, Thailand

Müller, Tim WC-16
Tim.mueller@fst.tu-Darmstadt.de
Chair of Fluid Systems, Technische Universität Darmstadt, Darmstadt, Germany

Ma, Tai-yu TB-12
tai-yu.ma@liser.lu
Urban Development and Mobility, Luxembourg Institute of Socio-Economic Research (LISER), Esch-sur-Alzette/Belval, Luxembourg

Mallor, Fermin TA-16
mallor@unavarra.es
Institute of Smart Cities, Public University of Navarre, Pamplona, Spain

Mansini, Renata WD-02
renata.mansini@unibs.it
Department of Information Engineering, University of Brescia, Brescia, Italy

Martin, Alexander TB-15
alexander.martin@math.uni-erlangen.de
Mathematics, FAU Erlangen-Nürnberg, Discrete Optimization, Erlangen, Germany

McKenna, Russell TA-08, TB-08, TD-09
russell.mckenna@abdn.ac.uk
University of Aberdeen, Aberdeen, United Kingdom

Megow, Nicole TA-07
nicole.megow@uni-bremen.de
Mathematik/Informatik, Universität Bremen, Bremen, Germany, Germany

Misconel, Steffi WE-08
steffi.misconel@tu-dresden.de
Chair of Energy Economics, TU Dresden, Germany

Author Index

SESSION INDEX

Wednesday, 9:00-10:20

Wednesday, 10:40-12:00

Wednesday, 13:00-14:20

Wednesday, 14:40-15:40

Wednesday, 16:00-17:20

Wednesday, 17:30-18:30

Thursday, 9:00-10:20

Thursday, 10:40-12:00

Thursday, 13:00-14:00

Thursday, 14:20-15:40

Thursday, 16:00-17:00

Friday, 9:00-10:20

Friday, 10:40-11:40

Friday, 12:00-13:00