

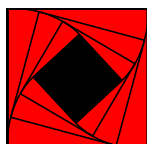
# NORM 2026

1st Nordic Operations Research Meeting

Stockholm, October 19–21, 2026



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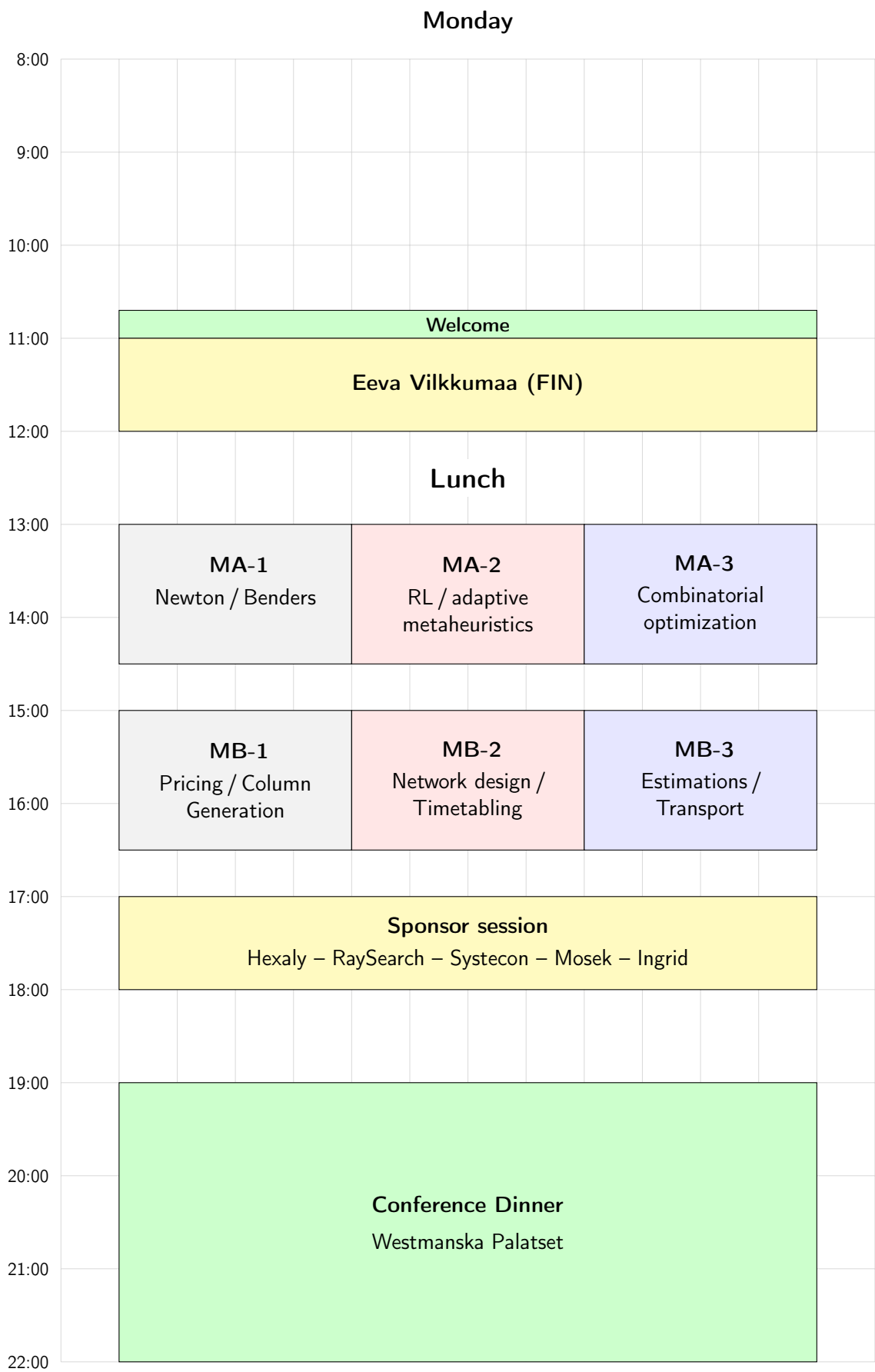
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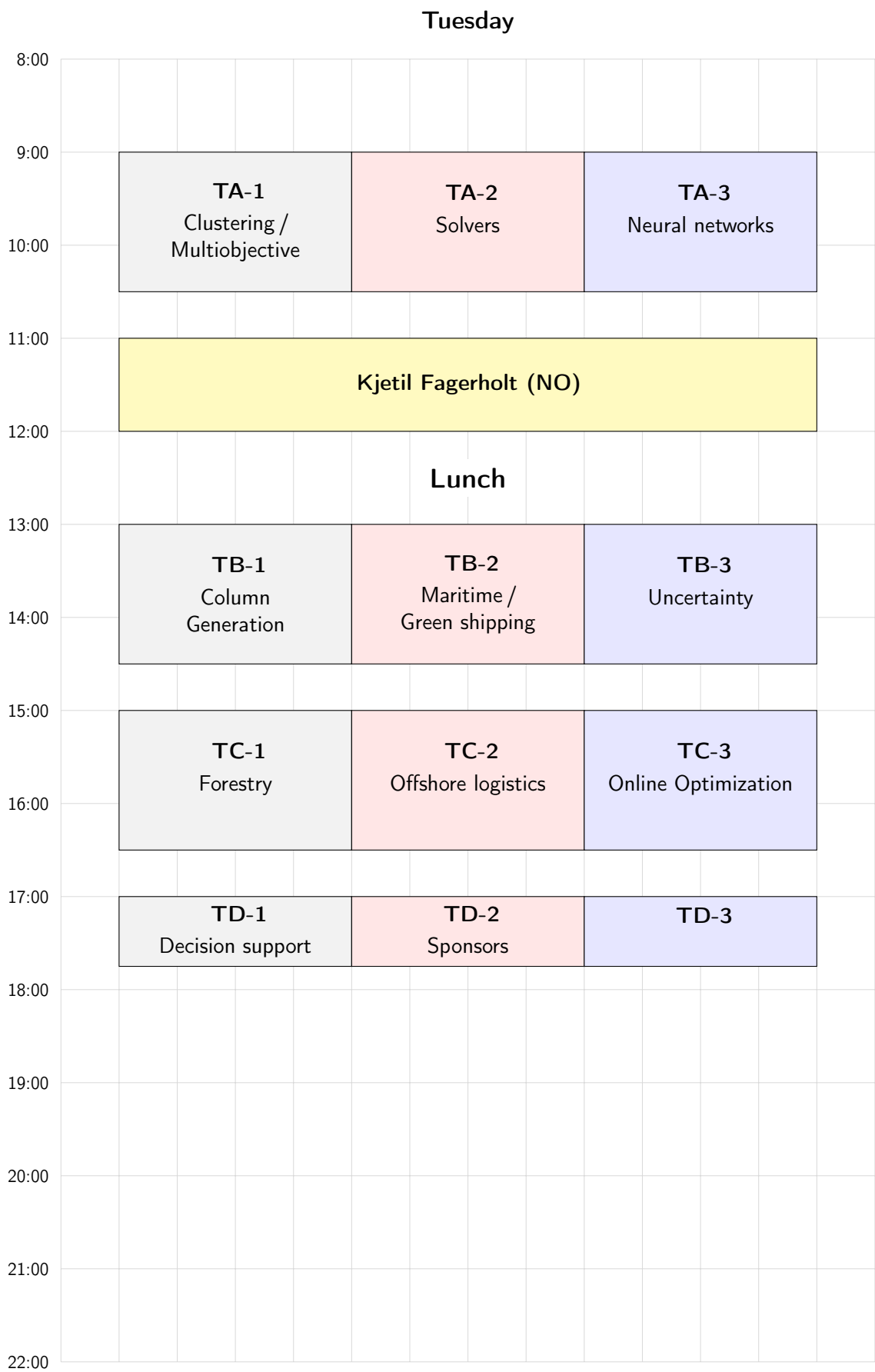
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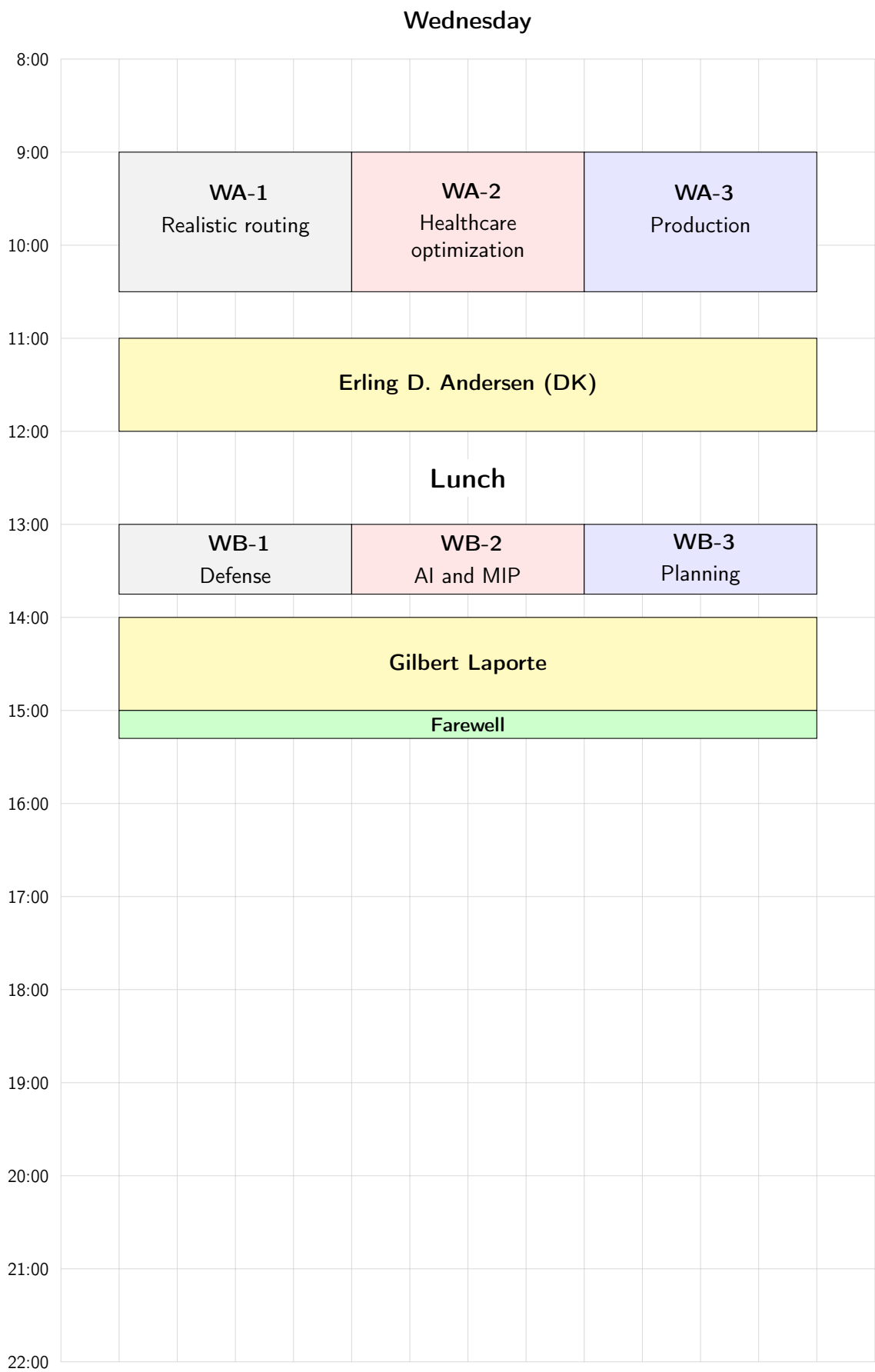
## Sponsors

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## Plenaries

### Monday: Eeva Vilkkumaa (Aalto University)

Operations Research for addressing deep uncertainty and sacred values

#### Abstract

Many high stakes business and policy decisions confront two challenges: deep uncertainty about how the future may unfold, and objectives tied to “sacred” values — such as health, safety, and the environment — that resist simple trade offs. Critics sometimes claim that analytic methods reflect technocratic arrogance or sideline human values. This plenary talk argues the opposite: when designed to be transparent, participatory, and robustness focused, Operations Research methods can materially improve decisions in these settings.

As evidence for this argument, I introduce a method that uses consistency analysis and optimization to construct a small, diverse set of plausible scenarios as a representation of deep uncertainty, and illustrate its use in developing scenarios for the Finnish National Emergency Supply Organization. I then present a scenario based decision model that combines portfolio decision analysis with robust optimization to identify strategic action portfolios that perform well across scenarios, drawing on a case study carried out with Nordea Bank. Finally, I report findings from a survey and an experiment on preference elicitation processes in the presence of sacred values, highlight common pitfalls in such processes, and provide tentative recommendations for best practices. I conclude the talk by discussing aspects in OR model building processes that merit special attention in contexts involving deep uncertainty and sacred values.

**Tuesday: Kjetil Fagerholt (NTNU and SINTEF Ocean)**

Reducing emissions with hybrid-electric supply vessels: The role of weather-aware operational planning

**Abstract**

Reducing greenhouse gas emissions from maritime transportation is an important challenge in the transition towards more sustainable transport systems. For platform supply vessels (PSVs), which transport supplies between onshore bases and offshore oil and gas installations, hybrid-electric propulsion combined with offshore charging represents a promising solution. However, realizing the emission-reduction potential of such vessels requires efficient operational planning, where routing, sailing speeds, charging decisions and power management must be optimized jointly. These decisions are further complicated by weather conditions, which influence energy consumption, sailing times and the feasibility of offshore operations.

In this keynote, we present the Hybrid-electric Weather-dependent Supply Vessel Routing Problem, which integrates these operational decisions while accounting for weather-dependent energy consumption and emission-reduction requirements. We briefly discuss a mathematical optimization model and alternative solution methods, including an Adaptive Large Neighborhood Search (ALNS) metaheuristic developed to solve realistic problem instances.

Using a case study based on Equinor's supply operations on the Norwegian Continental Shelf, we investigate the computational performance of the proposed solution methods and explore the operational and economic implications of hybrid-electric PSVs. The results demonstrate the importance of optimizing sailing speeds and incorporating weather information into operational planning. We also examine how emission-reduction requirements and battery capacities influence operational costs and the economic attractiveness of electrification.

The keynote illustrates how operations research can contribute to maritime decarbonization by enabling more efficient utilization of emerging green technologies.

**Wednesday: Erling D. Andersen (DK)**

My career in operations research

**Abstract**

I became a member of DORS approximately 35 years ago, and have therefore been involved in operations research (OR) for a long time. During these years, I have spent most of my time working on optimization, particularly developing optimization software used by researchers and practitioners in the OR community.

In this presentation, I will discuss my career in operations research, including my work in founding MOSEK, a company that develops optimization software for solving large-scale optimization problems. I will also reflect on some of the challenges, experiences, and lessons I have encountered along the way.

**Wednesday: Gilbert Laporte (HEC Montréal, University of Bath, Molde)**

A Short History of the Traveling Salesman and Its Influence on the Field of Combinatorial Optimization

**Abstract**

I will provide a short history of the Traveling Salesman Problem (TSP), starting with the solution of the knight's problem by Leonhard Euler in 1759, and ending with a very efficient implementation of the Lin and Kernighan heuristic by Taillard and Helsgaun in 2019. The talk covers the main exact and heuristic algorithms that have been developed for the undirected and directed cases of the TSP. I will emphasize the influence that the study of the TSP has had on the evolution of the field of combinatorial optimization.

## Presentations

**MA: 13.00 – 14.30**

### **MA-1: Newton / Benders**

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1. On Modified Newton Methods for Unconstrained Optimization Based on the Lanczos Tridiagonalization, Aban Ansari-Önnestam (LiU)
  2. A higher-order extrapolation primal-dual interior-point method, Pim Heeman (KTH)
  3. Introducing automatically derived subproblem relaxations in a logic-based Benders decomposition solver, Sachin Rajendran (LiU)
  4. Strengthening a Logic-based Benders Approach for Routing and Scheduling of Time-Sensitive Networks, Jesper Vines (LiU)
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### **MA-2: Reinforcement Learning / Adaptive metaheuristics**

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5. Learning-based Evolutionary Path Relinking for the Capacitated Close-enough Facility Location Problem, Arild Hoff (Molde)
  6. A Reinforcement Learning Based Hyperheuristic Framework for Multi-Objective Combinatorial Optimisation, Eirik Petrie (Bergen)
  7. State, Action, and Reward Design for Reinforcement Learning-Enhanced Adaptive Large Neighborhood Search in Periodic Supply Vessel Planning, Tsimafei Nemytau (Molde)
  8. Learning to stow RoRo vessel. A reinforcement learning success story, Dario Pacino (DTU)
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### **MA-3: Combinatorial Optimization**

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9. Generalised Clause Learning for Constraint Programming, Justin Pearson (UU)
  10. A general algorithmic pattern for finding lexicographic max-ordering solutions to combinatorial multicriteria optimization problems, Zoe Dumoulin (UU)
  11. A Tight 2-Approximation for Demand Bin Packing, Albert Vesterlund (Chalmers)
  12. Undirected Variants of the Minimum Flow Decomposition Problem, Philine Schiewe (Aalto)
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**MB: 15.00 – 16.30**

**MB-1: Pricing / Column Generation**

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13. Heuristic pricing by ML-guided subgraph construction in Column Generation for Vehicle Routing Problems, Lukas Eveborn, LiU.
  14. Electric vehicle routing at Traton - A column generation approach, Gabrijela Obradović, Scania.
  15. Fast Exact Computation of Wasserstein Barycenters via Multimarginal Optimal Transport and Column Generation, Alfred Wärnsäter, KTH.
  16. Robust Chance-Constraints for Electric Vehicle Routing Problems, Jan Rolfes, LiU.
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**MB-2: Network design / Timetabling**

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17. Incorporating Municipal Competition and Investment into Bus Rapid Transit Network Design and Stop Selection, Michael Sederlin, VTI.
  18. Ferry traffic optimization for regional transport planning, Bernardo Martin-Iradi, VTI.
  19. Long-term planning of railway capacity restrictions and traffic flow adaptations, Tomas Lidén, VTI.
  20. Carbon-Aware Ferry Timetabling and Skip-Stop Planning under Land-based Travel Alternatives, Youkai Wu, Bergen.
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**MB-3: Estimations / Transport**

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21. Computation of low rank approximations of matrix polynomials using regularization, Jenny Enerbäck, Chalmers.
  22. Estimation of dynamic shaft torque in maritime propulsion systems using regularized least-squares, Urho Hakonen, Aalto.
  23. Marine Engine Virtual Torque Sensor using Cylinder Pressure Measurements, Aksel Ilveskero, Aalto.
  24. The optimal transport problem with an occupation constraint, Johan Karlsson, KTH.
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**TA: 9.00 – 10.30****TA-1: Clustering / Multiobjective**

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- 25. An efficient mixed-integer linear programming formulation for solving influence diagrams, Topias Terho, Aalto.
  - 26. A Novel Transparency-Oriented Approach to Fairness in Cluster Analysis, Ansgar Boss Henrichsen, CBS.
  - 27. Computing Stochastically Non-Dominated Decision Trajectories in Discrete Multi-Criteria Decision Problems, Leevi Olander, Aalto.
  - 28. The Role of Objective Functions and Solvers in Payload-Dependent Multi-Trip UAV Cargo Routing, Abdullah Tunc Buyuksan, Ankara.
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**TA-2: Solvers**

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- 29. Connecting Constraint Qualifications, Cycling and Numerical Accuracy in the Outer Approximation algorithm, Erik Tamm, KTH.
  - 30. What's new in SHOT 2.0, Andreas Lundell, Åbo.
  - 31. Preconditioned Parallel Solvers for Mean Field Games, Heidi Wolles Ljósheim, Edinburgh.
  - 32. What's new in HiGHS, Julian Hall, Edinburgh.
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**TA-3: Neural networks**

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- 33. Multi-horizon optimization with embedded neural networks, Michal Kaut, SINTEF.
  - 34. ICNN-enhanced 2SP: Leveraging input convex neural networks for solving two-stage stochastic programming, Fabricio Oliveira, DTU
  - 35. Neural Surrogates for Bilevel MIP, Axel Kärrholm, KTH.
  - 36. Beyond fully input convex networks: tractable surrogate-based optimisation with the input convex neural network class, Yu Liu, Aalto.
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**TB: 13.00 – 14.30****TB-1: Column Generation**

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37. A Column Generation Methodology for Electric Air Transport Network Design Optimization, Eyrún Aradóttir, VTI.
  38. The Primal-Dual Hybrid Gradient Method for Column Generation in Vehicle Routing, Joseph Löfving, Chalmers.
  39. Optimizing persistent surveillance missions for UAVs by column generation, William Stenberg, Saab.
  40. A Column Generation Approach for Noise-Aware Drone Routing with Operational Costs, Haoye Chen, KTH.
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**TB-2: Maritime / green shipping**

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41. Operational Impacts of Green Fuels on Feeder Liner Shipping, Mohamed Kais Msakni, NTNU.
  42. Norway's Coastal Express as a green corridor: Optimal power system selection and bunkering infrastructure planning, Kenneth Løvold Rødseth, Oslo.
  43. Adapting Liner Shipping Networks to Seasonal Arctic Route Availability, Gleb Sibul, NTNU.
  44. Matheuristic for a Rich Feeder Network Design problem, Anandhu Dileep, Bergen.
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**TB-3: Uncertainty**

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45. Diversification in multi-period portfolio optimization, Homayoun Shaabani, Molde.
  46. Adaptive Weather Routing for Wind-Propelled Vessels under Forecast Uncertainty, Martin Augestad, NTNU.
  47. Robust Medium-Term Hydropower Production Planning using Affine Decision Rules, Gunnar Lidestam, LiU.
  48. Operational planning of technician assignment and task allocation to vessels for offshore wind farm maintenance under service time uncertainty, Vibeke Hvidegaard Petersen, NTNU.
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**TC: 15.00 – 16.30****TC-1: Forestry**

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- 49. Timbertrail - a decision support tool for efficient harvest planning, Erik Klein, Creative Optimization.
  - 50. Electrification of forest logistics, Mikael Rönqvist, Laval.
  - 51. Dynamic Game-Theoretic Analysis of Strategic Pricing in the Swedish Pulpwood Market, Soleiman Mohammadi Limaie, MittU
  - 52. Bi-objective optimization for dairy farm operations to balance profit and greenhouse gas emissions, Julio Cesar Goetz Gutierrez, Bergen.
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**TC-2: Offshore logistics**

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- 53. Tactical offshore personnel transportation planning on the norwegian continental shelf uses optimized models to match weekly transport demand with helicopter fleets, Vladislav Klyuev, Molde.
  - 54. Crew Transfer Vessels Routing for Offshore Wind Farm Maintenance: Impacts of Electric Vessel Charging Consideration, Paulo Cesar Ribas, Molde.
  - 55. Emissions estimation in offshore logistics planning: insights into Offshore Maritime Logistics Optimisation Workbench, Victoria Gribkovskaia, SINTEF.
  - 56. Optimizing Battery Utilization in Hybrid Offshore Support Vessels: Evidence from Operational Data, Gabriel Fuentes, Bergen.
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**TC-3: Online optimization**

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- 57. Threshold-Safe Dynamic Release Scheduling under Finite Recovery, Aleksandr Omelchenko, Bremen.
  - 58. Dynamic Offering and Pricing of Mixed Last-Mile Delivery Options via Approximate Dynamic Programming, Ze Zhou, Chalmers.
  - 59. Dynamic flow synchronisation of perishable goods, Brede Sørøy, Oslo.
  - 60. Online Distributed Learning with Sublinear Regret for Virtual Reality Networks, Rebecka Haraldsson, KTH.
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**TD: 17.00 – 17.45****TD-1: Decision support**

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- 61. Operations Research for Tactical Command and Control: An Integrated Decision-Support Pipeline for Course-of-Action Evaluation, Cengizhan Dogan, Eper Technologies.
  - 62. Multiobjective Grey-Box Optimization with Applications in the Mining Industry, David A. Liñán, KTH.
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**TD-2: Sponsors**

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- H. Hexaly: the next-generation MIP solver
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**WA: 9.00 – 10.30****WA-1: Realistic routing**

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- 63. Flexible Electric Vehicle Charging with Karma, Ezzat Elokda, KTH.
  - 64. Integrating Operational Considerations into the Dynamic-Arrival-Routes Framework, Roghayeh Hajizadeh, LiU.
  - 65. What do delivery drivers know, that optimization algorithms don't?, Sophie Blum, Bergen.
  - 66. MILP Formulation for a Rich Multi-Depot Pickup-and-Delivery Problem with Trailer Operations, Driver Regulation, and Equipment Compatibility, Magnus Levinsen, DTU.
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**WA-2: Healthcare optimization**

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- 67. Delivery Efficiency in Upright Radiotherapy: Bidirectional Chair Rotation in Upright Static Carbon Arcs, Wouter van Weerelt, RaySearch.
  - 68. Choosing prevention strategies for cardiovascular diseases with the aid of the Saari triangle, Jaakko Hakula, Kempele.
  - 69. A Column Generation Approach for Automated Planning of 3D-Printed Applicators in Skin Brachytherapy, Björn Morén, LiU.
  - 70. Robust Patient Ordering in Shared-beam Ion Radiotherapy, Viktor Wase, RaySearch.
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**WA-3: Production**

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- 71. Flexible Capacity Strategies for Resource-Constrained Multi-Project Scheduling, Mohamed Ben Ahmed, Molde.
  - 72. Order-Book Balancing at Scania: Optimization Support for Production Levelling, Saeed Mohammadi, Scania.
  - 73. Optimization approaches for long-term structural and operational planning in integrated steel plants, Carl Haikarainen, Åbo.
  - 74. Integrated Balancing and Scheduling of Mixed-Model Human-Robot Collaborative Assembly Lines with Mobile Workers, Pedram Beldar, Skövde.
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**WB: 13.00 – 13.45****WB-1: Defense**

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- 75. A time expanded network formulation for planning of air defense missions, Kristoffer Tondel, Saab.
  - 76. Persistent Scenario Classes for Defense Planning via Formal Concepts and Optimization, Torgeir Aambø, FFI.
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**WB-2: AI and MIP**

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- 77. An illustrative instance of an Artificial Intelligence Planning Problem formulated as an Integer Problem, Vortechz Andersson, Vortechz AB.
  - 78. Neural Networks as Mixed Integer Programs: Formulations and Use Cases, Johanna Skåntorp, KTH.
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**WB-3: Planning**

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- 79. Operationalizing a Prospective Assessment Framework for Regional CCS Value Chain Planning under Uncertainty, Volodymyr Kartashov, Molde.
  - 80. Can less efficient turbines be used to improve wind farms?, Martin Dragseth Gregusson, Bergen.
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# 1. On Modified Newton Methods for Unconstrained Optimization Based on the Lanczos Tridiagonalization

Aban Ansari-Önne<sup>1</sup>, Anders Forsgren<sup>2</sup>, Philip E. Gill<sup>3</sup>

<sup>1</sup> Linköping University, Linköping, Sweden

<sup>2</sup> KTH Royal Institute of Technology, Stockholm, Sweden

<sup>3</sup> University of California, San Diego, San Diego, United States

## Abstract | $\Rightarrow$

Newton's method with a line search offers rapid convergence to an unconstrained minimizer by incorporating second-order information when strong convexity holds. However, for a general optimization problem the Hessian need not be positive definite, which can lead to the inability to find a search direction or search directions that fail to produce descent. This talk concerns modifications to the Newton-CG approach based on the Lanczos tridiagonalization. We modify the Hessian within a conjugate-gradient framework to guarantee a descent direction while keeping the modifications bounded. We further explore how the convergence and computational cost is affected by varying the amount of curvature introduced and allowing the early termination of the inner iterations.

## 2. A higher-order extrapolation primal–dual interior-point method

Pim Heeman<sup>1</sup>, Anders Forsgren<sup>1</sup>

<sup>1</sup> KTH Royal Institute of Technology, Stockholm, Sweden

### Abstract | $\Rightarrow$

Interior-point methods transform a smooth optimization problem into a problem without explicit inequality constraints by a logarithmic barrier transformation. This gives an approximate problem where the accuracy of this approximation is controlled by a positive scalar, the barrier parameter. Problems are solved for a sequence of decreasing barrier parameters, warm-starting the problem for the current parameter with the solution for the previous. A trade-off is to be made between decreasing the barrier parameter fast enough to not solve a problem for a fixed barrier parameter more accurately than necessary on one hand and ensuring that a perturbed problem is not changed too drastically that warm-starting helps significantly on the other hand. In this talk, an accelerator for primal–dual interior-point methods following this scheme for general nonlinear problems is proposed that uses higher-order derivatives, for asymptotic convergence at a rate proportional to the order of derivatives used. For quadratic programming, parallels can be drawn between a proof-of-concept method and the Mehrotra predictor–corrector method and computational results will accordingly be shown. Computational results on general nonlinear test problems associated with CUTEst will also be shown, for which a SIF parser allowing access to higher-order derivatives has been developed.

### 3. Introducing automatically derived subproblem relaxations in a logic-based Benders decomposition solver

Sachin Rajendran<sup>1</sup>, Stephen Maher<sup>2</sup>, Elina Rönnberg<sup>1</sup>

<sup>1</sup> Linköping University, Linköping, Sweden

<sup>2</sup> Gams, Germany, Germany

#### Abstract | $\Rightarrow$

Logic-based Benders decomposition (LBBD) effectively combines mixed integer programming and constraint programming to solve difficult optimisation problems. While the decomposition exploits different solution and modelling paradigms, the separation destroys problem information connecting master and subproblem decisions. Alongside cut generation, a standard way of re-introducing this connection is through the addition of valid inequalities in the master problem. These inequalities typically constitute subproblem relaxations and they are usually problem specific and derived by hand. This paper proposes a general approach for deriving valid inequalities and demonstrates how they can be applied to cumulative and disjunctive constraints. In an effort to develop a general purpose LBBD solver, the general derivation of valid inequalities have been implemented as part of a new cumulative constraint handler for SCIP and the effectiveness is evaluated on two variants of scheduling problems. The computational experiments show the potential of applying these general valid inequalities to the master problem.

## 4. Strengthening a Logic-based Benders Approach for Routing and Scheduling of Time-Sensitive Networks

Jesper Vines<sup>1,2</sup>, Hannes Uppman<sup>3</sup>, Elina Rönnberg<sup>1</sup>

<sup>1</sup> Linköping University, Linköping, Sweden

<sup>2</sup> Saab AB, Stockholm, Sweden

<sup>3</sup> Saab AB, Linköping, Sweden

### Abstract | $\Rightarrow$

In the electronic system in an aircraft, the avionics system, a large number of data packages need to be reliably transmitted and received on time. An important part in achieving this reliability can be to statically decide how to route the packages through the network and to fix a schedule for when each package should be sent to the next node in its path. The standards of Time-Sensitive Networking (TSN) enable guarantees regarding latency and availability of such scheduled data. However, a challenging optimisation problem for the routing and scheduling needs to be solved. As the sizes of avionic systems are likely to increase, the methods for solving these joint routing and scheduling problems need to scale well.

We propose a logic-based Benders decomposition scheme for joint routing and scheduling in a TSN network. A natural decomposition of this problem, where message routing is decided in the master problem and the remaining scheduling problem is solved in the subproblem, has been proposed in earlier work [Vik et al., Comput. Ind. Eng. 157 (2021)]. For larger problem instances, this decomposition can lead to subproblems that are very hard to solve, or determine infeasibility of. We therefore extend this method with acceleration strategies to solve larger problem instances.

These strategies include strengthening the master problem by introducing additional decisions, such as assigning time-slots to the packages and enforcing no-wait conditions, aimed at reducing the size of the subproblem. We also iteratively solve subproblem relaxations to identify infeasibility earlier.

## 5. Learning-based Evolutionary Path Relinking for the Capacitated Close-enough Facility Location Problem

He Zheng<sup>1</sup>, Anna Martínez-Gavara<sup>1</sup>, Arild Hoff<sup>2</sup>, Rafael Martí<sup>1</sup>

<sup>1</sup> Department of Statistics and Operations Research, University of Valencia, Valencia, Spain

<sup>2</sup> Faculty of Logistics, Molde University College, Molde, Norway

### Abstract | $\Rightarrow$

In this research, we address the Capacitated Close-Enough Facility Location Problem, in which customers can be served either directly by open facilities or indirectly through capacitated pickup points located within a prescribed distance. This problem has attracted a lot of attention because of its practical relevance in modern distribution systems.

However, existing approaches become increasingly expensive as instance sizes grow. To address this limitation, we propose a hybrid metaheuristic that combines diversified construction strategies, tabu search, and path relinking. A contextual multi-armed bandit mechanism is further incorporated to adaptively select reference elite solutions during the relinking phase.

Computational experiments on 225 benchmark instances show that the proposed algorithm is highly competitive. It matches the best known solution on all instances, achieves very small average deviations over independent runs, and requires significantly less computational time than reference methods.

## 6. A Reinforcement Learning Based Hyperheuristic Framework for Multi-Objective Combinatorial Optimisation

Eirik Petrie<sup>1</sup>, Ahmad Hemmati<sup>1</sup>

<sup>1</sup> University of Bergen, Bergen, Norway

### Abstract | $\Rightarrow$

Many real-world combinatorial optimisation problems are multi-objective, where the aim is not a single optimum, but a set of trade-off solutions. Adaptive Large Neighbourhood Search is a flexible framework for combinatorial optimisation, but in its standard form the adaptive layer is usually limited to choosing low-level heuristics. When ALNS is combined with decomposition-based multi-objective search, the scalarisation weights also matter, since they guide the search towards different regions of the objective space.

This paper studies whether reinforcement learning can control both heuristic selection and search-direction adaptation. We present DRLMOH, a reinforcement-learning-based multi-objective hyperheuristic that combines ALNS with decomposition-based search. The method maintains a population of search agents, each with its own solution and scalarisation weight vector. A shared policy selects removal and insertion heuristics, destroy sizes, and small online adjustments to the weight vectors. This allows each agent to search around its assigned direction, rather than being restricted to a fixed scalarisation throughout the run.

The method is evaluated on a set of multi-objective combinatorial optimisation problems, with experiments designed to test both heuristic selection and adaptive search-direction control. It is compared against decomposition-based ALNS variants, epsilon-constrained ALNS, and an ablation where the learned policy cannot adjust the weight vectors.

Preliminary results suggest that the reinforcement-learning policy improves the quality and stability of the approximation sets, and that adaptive weight control contributes to this improvement. The results indicate that reinforcement learning can be used not only to select heuristics, but also to guide decomposition-based multiobjective search.

## 7. State, Action, and Reward Design for Reinforcement Learning-Enhanced Adaptive Large Neighborhood Search in Periodic Supply Vessel Planning

Tsimafei Nemytau<sup>1</sup>, Irina Gribkovskaia<sup>1</sup>, Gilbert Laporte<sup>2</sup>

<sup>1</sup> Molde University College, Molde, Norway

<sup>2</sup> HEC Montréal, Montreal, Canada

### Abstract | $\Rightarrow$

Integrating reinforcement learning (RL) into metaheuristic search has emerged as a promising direction for combinatorial optimization, yet the effect of RL problem formulation on algorithm behavior remains poorly understood. This work systematically studies how state representation, actionspace design, and reward shaping affect the behavior and effectiveness of RLenhanced Adaptive Large Neighborhood Search (ALNS).

The study focuses on the Periodic Supply Vessel Planning Problem (PSVPP), which seeks costminimal repeating schedules for offshore supply vessels serving installations on the Norwegian Continental Shelf. ALNS relies on destroyandrepair operators whose selection critically influences search performance — making it a natural candidate for RLbased control, but one where formulation choices are far from obvious.

This work addresses the question: which RL formulation choices — state representation, actionspace design, and reward shaping — most strongly influence the performance of RLenhanced ALNS? Through controlled experiments on benchmark instances generated to reflect realworld PSVPP characteristics, we compare alter native state encodings, actionspace formulations — joint versus independent operator selection — and reward signals based on immediate improvement, relative gain, and longhorizon solution quality, measuring their impact on convergence speed and solution quality. Particular attention is given to generalization across heterogeneous problem instances, a key requirement for practical deployment.

The results are expected to provide actionable design guidelines for embedding RL into metaheuristic frameworks and inform future extensions of the approach toward stochastic variants of the PSVPP.

## 8. Learning to stow RoRo vessel. A reinforcement learning success story.

Dario Pacino<sup>1</sup>, Oliver Thomsen<sup>1</sup>

<sup>1</sup> Technical University of Denmark (DTU), Kgs. Lyngby, Denmark

### Abstract | $\Rightarrow$

Stowage planning is the art of deciding where cargo should be placed on a vessel. A Roll-On Roll-Off (RoRo) vessel is what most people would refer to as a ferry. You drive on at arrival (Roll-On) and drive off at departure (Roll-Off). Ferries are planned on the fly, and this is possible because most of the vehicles on a ferry have an easily foreseeable weight and size. A RoRo vessel for freight transport is similar, but cargo weights and size can vary drastically. Weight, in particular, can range from 10 to 80 tons. Placing an 80-ton paper-roll trailer wrongly, could drastically impact vessel stability, fuel consumption, and ultimately emissions. This talk will present how Reinforcement Learning can be used to learn a policy for fast stowage decision making. We demonstrate the Reinforcement Learning can efficiently be used to generate feasible stowage plans for direct industrial application. The model is able to handle realistic stability constraints, hazardous cargo handling, and the minimization of ballast water. The Reinforcement Learning model presented is based on a transformer architecture and make use of PolyNet as a learning algorithm. We also show how the use of PolyNet helps generalizing the results, compared to the more traditional Actor-Critic methods.

## 9. Generalised Clause Learning for Constraint Programming

Justin Pearson<sup>1</sup>

<sup>1</sup> Uppsala universitet, Uppsala, Sweden

**Abstract** |  $\Rightarrow$

In this talk, I will present a generalisation of conflict-driven clause learning (CDCL) for constraint programming over abstract domains. A core idea in constraint programming is propagation: each constraint has an associated algorithm that during search prunes potential non-solutions. The abstract theory of constraint propagators as idempotent, monotonic, contracting functions over partial orders has led to the development of propagators and solvers over non-integer domains, such as strings, sets or floating point numbers. Building on this theory, I introduce a generalisation of reasons, explanations, and implication graphs from CDCL to propagation-based solving over abstract domains. A central result shows that cuts in the implication graph are no-goods. An abstract scheme is presented that unifies CDCL solving from SAT and lazy-clause search from constraint programming.

## 10. A general algorithmic pattern for finding lexicographic max-ordering solutions to combinatorial multicriteria optimization problems

Zoe Dumoulin<sup>1</sup>, María Andreína Francisco Rodríguez<sup>1</sup>, Filip Malmberg<sup>1</sup>

<sup>1</sup> Uppsala University, Uppsala, Sweden

### Abstract | $\Rightarrow$

We study a particular class of greedy algorithms for combinatorial optimization problems and present a generalized version of this algorithmic pattern encompassing several previously published algorithms. We analyze the structural properties of the solutions produced by such algorithms, and provide proofs of their optimality through the concept of lexicographic max-ordering. Because this solution concept guarantees both max-ordering and Pareto optimality in multicriteria optimization, utilizing it allows our algorithmic pattern to bridge the gap between independently developed algorithmic structures.

Our unified formulation provides both a conceptual foundation for this class of greedy algorithms and a practical basis for designing new ones. To demonstrate its applicability, we present two case studies: correlation clustering via the mutex watershed algorithm and binary graph labeling via the Malmberg–Ciesielski algorithm. We show that both can be interpreted as instances of our framework, yielding alternative proofs of correctness and new insights into their structural properties.

## 11. A Tight 2-Approximation for Demand Bin Packing

Debajyoti Kar<sup>1</sup>, Arindam Khan<sup>1</sup>, Malin Rau<sup>2</sup>, Ann-Brith Strömberg<sup>2</sup>, Albert Vesterlund<sup>2</sup> Sweden

<sup>1</sup> Indian Institute of Science, Bengaluru, India

<sup>2</sup> Department of Mathematical Sciences, Chalmers University of Technology & University of Gothenburg, Gothenburg,

### Abstract | $\Rightarrow$

We study the Demand Bin Packing problem, where we are given an unlimited supply of identical bins (machines), each with fixed time horizon and resource capacity, and a set of items. Each item (job) is characterized by a processing time and a resource demand. The objective is to assign all items to as few bins as possible so that, at any time in each bin, the total demand of items active at that time does not exceed the bin capacity. Each item represents a rectangle whose width equals its processing time and whose height equals its demand, while each bin corresponds to a unit square. Rectangles may be sliced vertically, but all slices of an item must occupy contiguous horizontal positions and cannot be stacked vertically. This problem generalizes classical Bin Packing and captures a broad range of demand allocation and scheduling settings.

We develop an asymptotic  $(1 + \ln(3/2) + \varepsilon)$ -approximation algorithm based on a new restructuring theorem showing that any optimal demand packing with a sufficiently large number of bins can be transformed into a structured packing at a loss of only a  $(3/2 + \varepsilon)$  factor. Combined with a Round-and-Approx framework using randomized rounding, we construct a configuration LP to obtain the improved asymptotic approximation.

We also present a tight absolute 2-approximation algorithm, resolving an open problem posed by Albers et.al (2025). Central is a structural result showing that if all items fit in one bin, a feasible packing using at most two bins can be constructed efficiently.

## 12. Undirected Variants of the Minimum Flow Decomposition Problem

Fernando Dias<sup>1</sup>, Philine Schiewe<sup>1</sup>

<sup>1</sup> Aalto University, Espoo, Finland

### Abstract | $\Rightarrow$

While finding a feasible flow decomposition in directed flow networks is a trivial task, determining a minimum number of paths decomposing a flow is NP-hard even for directed acyclic graphs. This property translates to undirected graphs, where we aim to find a minimum set of paths that covers every edge within a given range. We show how this new problem variant can be used to model multiassembly problems in genome reconstruction as well as line planning problems in public transport. To solve the problem, we propose a mixed-integer linear programming formulation. The formulation is tested on biological data as well as transport data.

### 13. Heuristic pricing by ML-guided subgraph construction in Column Generation for Vehicle Routing Problems

Lukas Eveborn<sup>1</sup>, Gunnar Lidestam<sup>1</sup>, Günther Raidl<sup>2</sup>, Elina Rönnberg<sup>1</sup>

<sup>1</sup> Linköpings Universitet, Linköping, Sweden

<sup>2</sup> TU Wien, Vienna, Austria

#### Abstract | $\Rightarrow$

For many vehicle routing problems, branch-price-and-cut is the state-of-the-art exact solution approach. A major computational bottleneck is the pricing phase, where an Elementary Shortest Path Problem with Resource Constraints (ESPPRC) is solved, typically using labeling algorithms.

This work introduces a heuristic pricing method, termed subgraph construction for column generation. Instead of solving the ESPPRC on the full graph, the pricing problem is solved on a collection of smaller subgraphs, reducing computational effort while aiming to retain high-quality columns.

We investigate two approaches for constructing subgraphs. The first is machine learning-based, using a graph neural network and a GFlowNet to learn a distribution over promising subgraphs. The second is based on problem-specific heuristics and structural insights.

Preliminary results on the electric vehicle routing problem with time windows suggest that the approach can accelerate pricing. However, the effectiveness of the method depends strongly on the quality of the generated subgraphs.

## 14. Electric vehicle routing at Traton – A column generation approach

Gabrijela Obradović<sup>1</sup>

<sup>1</sup> Scania/Traton, Stockholm, Sweden

### Abstract | $\Rightarrow$

Electrification introduces new operational challenges in vehicle routing, as route feasibility depends not only on customer assignment and travel time, but also on battery limitations, charging opportunities and driving time regulations. We study an electric vehicle routing problem in which a fleet of electric vehicles must serve a set of customers while minimizing total distance traveled. Customers are characterized by their individual demands and time windows within which the demands are to be served.

We propose a column generation approach in which the master problem selects feasible routes for vehicles so that each customer is served exactly once. Since enumeration of solutions is computationally intractable, routes are generated iteratively and come as a result of solving a number of individual and independent subproblems. The subproblems are typically elementary shortest path problems with resource constraints and are solved using labeling algorithms. While there exist solutions that have potential to improve the overall solution, the solution space is enlarged.

The proposed approach combines the decomposition strength of column generation with a detailed operational model for electric vehicle routing, providing a framework for fleet optimization under energy and regulatory constraints.

## 15. Fast Exact Computation of Wasserstein Barycenters via Multimarginal Optimal Transport and Column Generation

Alfred Wärnsäter<sup>1</sup>, Axel Ringh<sup>2</sup>, Johan Karlsson<sup>1</sup>

<sup>1</sup> KTH Royal Institute of Technology, Stockholm, Sweden

<sup>2</sup> Chalmers University of Technology, Gothenburg, Sweden

### Abstract | $\Rightarrow$

The Wasserstein barycenter is a geometrically meaningful notion of average for collections of probability measures, with applications in statistics, image processing, and economics. Computing Wasserstein barycenters is challenging, as the support of the barycenter must be selected from exponentially many candidate atoms. We study the exact computation of 2-Wasserstein barycenters of discrete measures on Euclidean space. Building on the well-known link to multimarginal optimal transport, we cast the problem as a linear program with exponentially many variables and solve it by column generation. Our central contribution is a novel exact pricing algorithm: we reformulate the pricing problem as a constrained non-convex quadratic program and, by decomposing its feasible set as a Minkowski sum of lifted polytopes, show that it admits only polynomially many candidate solutions, which can be enumerated via convex-hull computations. This also yields an alternative proof that computing 2-Wasserstein barycenters is polynomial-time solvable in fixed dimension. We combine this exact pricing routine with an inexpensive heuristic pricing scheme to obtain a dynamic column-generation algorithm that, depending on the choice of hyperparameters, computes either exact or approximate barycenters, trading off accuracy against computational cost. Because exact pricing produces a valid lower bound, the algorithm also yields optimality gaps and certificates of optimality. The method is easy to implement, and numerical experiments demonstrate that it is significantly faster than prior algorithms, enabling the exact computation of barycenters on previously intractable scales.

## 16. Robust Chance-Constraints for Electric Vehicle Routing Problems

Jan Rolfes<sup>1</sup>, Lukas Eveborn<sup>1</sup>, Elina Rönnberg<sup>1</sup>

<sup>1</sup> Linköping University, Linköping, Sweden

### Abstract | $\Rightarrow$

When solving the electric vehicle routing problem (EVRP) in practice, several aspects need to be considered. One of these is to account for uncertainties with regards to the energy consumption, e.g. varying weather conditions, vehicle conditions, and driving style, and how these affect the quality of the routing. As these uncertainties have the potential to perturb the solution space of an underlying vehicle routing problem significantly, we aim to find robust routes that remain feasible under these perturbations.

A common approach to address the size and challenges of solving EVRPs is to use branch-and-price algorithms. These algorithms decompose EVRP into a master problem over a subset of considered routes and a subproblem — the pricing problem — that computes promising routes by e.g solving elementary shortest path problems with resource constraints via labeling algorithms. However, the quality of a route as determined in the pricing problem is affected by the above uncertainties. Hence, we present a protection approach for the pricing problem that is based on robust chance constraints, i.e., that guarantees the feasibility of the computed route with a certain probability even if the probability distribution is not exactly known. Furthermore, we discuss a tractable conservative approximation of the robust chance constraints, thereby enabling an efficient handling in labeling algorithms for EVRP.

## 17. Incorporating Municipal Competition and Investment into Bus Rapid Transit Network Design and Stop Selection

Michael Sederlin<sup>1,2</sup>, Tygo Nijsten<sup>3,4</sup>, Aliki Poulisi<sup>5</sup>

<sup>1</sup> VTI, Stockholm, Sweden

<sup>2</sup> Linköping University, Norrköping, Sweden

<sup>3</sup> University of Amsterdam, Amsterdam, Netherlands

<sup>4</sup> Netherlands Organisation for Applied Scientific Research (TNO), The Hague, Netherlands

<sup>5</sup> National Technical University of Athens, Athens, Greece

### Abstract | $\Rightarrow$

Bus Rapid Transit (BRT) lines offer a fast and reliable alternative to conventional bus systems at a lower cost than rail infrastructure. They can enhance public transportation and promote sustainable travel, but require significant investments, including upgraded stops. Like many large-scale infrastructure projects, BRT initiatives often span multiple administrative regions, involving stakeholders with divergent objectives. Ignoring these differences can mask inequities in network redesign and create barriers to project implementation. In this paper, we present a (0,1)-Integer Linear Program (ILP) model for jointly selecting routes and stop upgrades for BRT lines, explicitly accounting for municipal competition and investment priorities. We evaluate multiple formulations of municipal utility through a case study in Copenhagen, Denmark. Results show substantial differences in efficiency, equity, and local investment costs across scenarios. Computational tests demonstrate that solution times remain practical for realistic network sizes (approximately 2–40 seconds), even when transfers, flexible stop demand, and new stops are considered.

## 18. Ferry traffic optimization for regional transport planning

Bernardo Martin-Iradi<sup>1</sup>, Tomas Lidén<sup>1</sup>

<sup>1</sup> VTI, Stockholm, Sweden

### Abstract | $\Rightarrow$

Ferry services are critical transport means in archipelago regions, yet planning is largely manual. We present an optimization model jointly planning ferry schedules, land connections, fleet assignments, and crew shifts, and we solve it via column generation on a space-time-shift network. The model balances operational costs and passenger and vehicle service levels, while respecting crew work regulations. Applied to a real-world case study, results show improvements in service quality, operational efficiency, and environmental impact relative to current planning.

## 19. Long-term planning of railway capacity restrictions and traffic flow adaptations

Tomas Lidén<sup>1</sup>, Johan Högdahl<sup>2</sup>

<sup>1</sup> VTI, Stockholm, Sweden

<sup>2</sup> RISE Sweden, Stockholm, Sweden

### Abstract | $\Rightarrow$

National planning of railway renewal and upgrade projects need to consider both the project completion aspects as well as their impact on the traffic throughput. Renewal and upgrade planning does however take place before the details of the railway traffic (i.e. the timetable) are known, which means that a more general traffic model is needed.

In a series of works a bi-level approach for solving this planning problem has been studied. The upper level schedules a set of projects, each consisting of a sequence of tasks with resource requirements and different types of capacity blockings on the traffic network. The lower level finds a traffic assignment, formulated as a path-based flow model, for a given traffic demand under the current capacity restrictions.

We present recent developments of this model approach that enable national multi-year planning of all major capacity restricting track works and the subsequent traffic adaptations for the complete planning period(s), based on a joint socioeconomical valuation of track works and traffic. Results from case studies of varying dimensions and complexity will be shown. Finally, we report ongoing work concerning implementation at the Swedish Transport Administration, and future development ideas.

## 20. Carbon-Aware Ferry Timetabling and Skip-Stop Planning under Land-based Travel Alternatives

Youkai Wu<sup>1</sup>, Mario Guajardo<sup>1</sup>, Kenneth L.Rødseth<sup>2</sup>, Kjetil Fagerholt<sup>3</sup>

<sup>1</sup> NHH Norwegian School Of Economics, Bergen, Norway

<sup>2</sup> Institute of Transport Economics, Oslo, Norway

<sup>3</sup> Norwegian University of Science and Technology, Trondheim, Norway

### Abstract | $\Rightarrow$

This study works on a timetabling problem with skip-stopping for passenger ferry services in Norway, with the objective of both reducing emissions and maintaining passenger service quality. While Norway's land-based public transport has largely achieved zero-emission operation, reducing emissions from passenger ferry services remains more costly, motivating more cost-effective decarbonization strategies. In the proposed problem, we jointly make decisions on how many trips to operate, when each trip departs, and which stops each trip serves or skips along a corridor. Passengers choose their travel mode between ferry and land-based on-demand mobility service, based on different settings of utility function. Based on this, a mixed-integer programming model is developed to optimize the passenger experience under a system-wide well-to-wheel emission cap, including emissions from both travel modes. We design an adaptive large neighborhood search algorithm to solve practical instances. The proposed framework provides a methodological framework for designing the timetable with skipstopping and evaluates impacts on passenger experience and carbon emissions.

## 21. Computation of low rank approximations of matrix polynomials using regularization

Jenny Enerbäck<sup>1</sup>, Andrii Dmytryshyn<sup>1</sup>, Ann-Brith Strömberg<sup>1</sup>

<sup>1</sup> Department of Mathematical Sciences at Chalmers University and Gothenburg University, Gothenburg, Sweden

### Abstract | $\Rightarrow$

The distance to singularity problem for matrix polynomials has received increasing attention in the last few years. One motivation for this interest is the need to solve complicated polynomial eigenvalue problems, e.g., singular eigenvalue problems. Applying standard methods designed for non-singular cases to singular cases can lead to catastrophic errors—many times without indication from the solvers that the results may be unreliable. One way to determine their reliability is therefore to verify regularity of the problem instance. However, since small perturbations almost always transform a singular instance to a non-singular instance, solely introducing a singularity check is not sufficient. A more robust measure is the distance to singularity.

In this presentation, we propose a new algorithm for approximating a given matrix polynomial with another matrix polynomial of rank at most  $r$  and also compute the distance from the given matrix polynomial to the computed approximation. Our algorithm covers the distance to singularity problem when the rank is chosen to be one less than the matrix size. We use randomization and regularization techniques and build on a recently developed algorithm which in turn is using generic eigenstructures, their parametrizations, and an alternating least squares scheme.

Our results show that our algorithm is typically faster than state-of-the-art methods, while showing a similar accuracy. This allows us to handle instances of larger size, as well as multiple initial guesses for small-to-medium size instances.

## 22. Estimation of dynamic shaft torque in maritime propulsion systems using regularized least-squares

Urho Hakonen<sup>1</sup>, Mikael Manngård<sup>2</sup>, Aksel Ilveskero<sup>1</sup>, Raine Viitala<sup>1</sup>

<sup>1</sup> Aalto University, Espoo, Finland

<sup>2</sup> Novia University of Applied Sciences, Åbo, Finland

### Abstract | $\Rightarrow$

Monitoring dynamic shaft torque in maritime propulsion systems is increasingly important for both condition monitoring and control related purposes. Reliable torque measurements provide valuable information on drive train loading, component health, and operational efficiency, while also supporting the prevention of propulsion failures, which remain a significant contributor to marine vessel casualties. The selection of an appropriate sensor location is constrained by accessibility, operating conditions, and the need to accurately capture the torsional response. Furthermore, dedicated torque sensing systems can have significant installation and maintenance costs. These limitations motivate the development of virtual sensing methods, in which dynamic shaft torque is estimated from readily available measurements and system models, offering a scalable alternative to direct instrumentation. This work presents the estimation of unknown external torques and torsional response of azimuthing maritime thrusters by utilizing convex optimization, namely, regularized least-squares. Convex optimization provides a flexible framework for incorporating physics-based constraints and prior knowledge into the estimation problem. It is shown that unknown torsional inputs and torsional response can be accurately estimated while promoting smoothness and robustness against measurement outliers. The method is validated with experiments on a testbench and measurements from a fullscale thruster.

## 23. Marine Engine Virtual Torque Sensor using Cylinder Pressure Measurements

Aksel Ilveskero<sup>1</sup>, Urho Hakonen<sup>1</sup>, Raine Viitala<sup>1</sup>

<sup>1</sup> Aalto University, Espoo, Finland

### Abstract | $\Rightarrow$

Monitoring the torsional dynamics of marine propulsion systems is critical for performance and safety, yet direct high-frequency torque measurements of the system remain costly and impractical. This paper proposes a Moving Horizon Estimation (MHE) framework to replace physical torque sensors by reconstructing the full internal state of a marine propulsion system from limited cylinder pressure and engine speed measurements. As the sensor data is sparse and noisy, and the model is assumed to be imperfect, optimization is necessary to obtain accurate results. The estimation is formulated as a quadratic optimization problem that minimizes measurement error and process noise over a sliding window. Additional regulating parameters are used to help constrain the solution: Trend filtering is used to smooth the unknown input load, while a Kalman Filter-based arrival cost connects historical data to the current window.

The optimization is implemented with a real-time-capable solver suitable for onboard deployment using regular, commercial computing hardware. A simple diesel engine powered propulsion system is modeled as a discrete linear state-space system through lumped-element modeling. A full simulated data set of internal shaft torques and element speeds is then constructed and used as a benchmark to measure the performance of the estimation. The MHE is shown to estimate the propeller shaft torque with a peak-to-peak Normalized Root Mean Squared Error (NMRSE) of 5.11%, using six cylinder pressure sensors and one encoder. Ultimately, this framework aims to provide a robust, cost-effective alternative to physical torque sensors in marine propulsion.

## 24. The optimal transport problem with an occupation constraint

Johan Karlsson<sup>1</sup>

<sup>1</sup> KTH, Stockholm, Sweden

**Abstract** |  $\Rightarrow$

We introduce new formulations of the dynamic optimal transport problem and the Schrödinger bridge problem for which the occupation measure is prescribed. In other words, we seek the most likely evolution connecting two probability distributions while constraining the process to realize a given spatial occupancy pattern. We establish duality results, develop computationally efficient solution methods, and demonstrate applications to trajectory inference in computational biology and to planning search-and-rescue missions.

## 25. An efficient mixed-integer linear programming formulation for solving influence diagrams

Topias Terho<sup>1</sup>, Fabricio Oliveira<sup>1,2</sup>, Ahti Salo<sup>1</sup>, Pedro Munari<sup>3</sup>

<sup>1</sup> Aalto University, Espoo, Finland

<sup>2</sup> Technical University of Denmark, Kongens Lyngby, Denmark

<sup>3</sup> Federal University of São Carlos, São Carlos, Brazil

### Abstract | $\Rightarrow$

Influence diagrams are directed graphs that represent decision problems involving interdependencies between uncertain events, decisions, and consequences. State-of-the-art methods convert an influence diagram into a mixed-integer linear programming (MILP) model solvable with off-the-shelf solvers, offering both computational power and the flexibility to incorporate alternative objectives and constraints. The leading approach, based on Rooted Junction Trees (RJT), performs very well on problems with a periodic structure that can be cast as partially observable Markov decision processes, but becomes inefficient when the influence diagram lacks this structure or contains nodes with large state spaces—a setting that arises frequently in practice, particularly when continuous variables must be finely discretized.

We present a reformulation of the Decision Programming MILP model (Salo et al., 2022, EJOR, 299(2)) that targets these challenging cases. By aggregating decision variables and introducing a valid inequality that tightens the linear relaxation, it yields substantial computational gains where existing approaches struggle. We demonstrate its effectiveness on decision problems from the literature. On influence diagrams that lack a periodic structure or have large state spaces, the formulation solves instances one to two orders of magnitude faster than existing methods and solves many otherwise intractable instances to optimality. On problems well suited to RJT, however, RJT often remains more efficient. The proposed formulation thus complements rather than replaces RJT.

## 26. A Novel Transparency-Oriented Approach to Fairness in Cluster Analysis

Ansgar Boss Henrichsen<sup>1</sup>, Dolores Romero Morales<sup>1</sup>

<sup>1</sup> Copenhagen Business School, Department of Economics, Frederiksberg, Denmark

### Abstract | $\Rightarrow$

Cluster Analysis is widely used in ML to uncover latent data patterns and identify groups of similar individuals in high-dimensional settings. As its role has grown and its applications have found their way into high-stakes decision-making, concerns about (un)fairness and the heterogeneous treatment of groups have started to arise. As a result of this, similar to the field of supervised learning, a range of fairness notions and new approaches to cluster analysis have been proposed to address these issues. However, blindly enforcing these notions can be detrimental to the very fairness objective being promoted, as well as to other fairness objections. We therefore propose a MIP mathematical optimization model that addresses this discrepancy of inappropriately enforced fairness notions for the case of a sensitive and a non-sensitive group. By providing representative prototypes for both groups and introducing so-called linking variables between them, we are able to improve the individual representation of both groups, as well as capture underlying group structures in the latent data space. This allows us to better understand the data we are working with, and to provide explanations for what drives the differences between the groups. We illustrate our approach using both simulated and real-world datasets.

## 27. Computing Stochastically Non-Dominated Decision Trajectories in Discrete Multi-Criteria Decision Problems

Leevi Olander<sup>1</sup>, Ahti Salo<sup>1</sup>

<sup>1</sup> Aalto University, Espoo, Finland

### Abstract | $\Rightarrow$

Discrete choice problems with multiple criteria and uncertain real-valued consequences are common, for example, in asset management, where alternatives can represent portfolios of maintenance actions. In such problems, first-order stochastic dominance can be readily employed as it does not require specific assumptions about the decision-maker's risk preferences beyond monotonicity. We present an algorithm to compute all first-order stochastically non-dominated probability distributions associated with the available alternatives in discrete multicriteria decision problems. Our algorithm, which builds on the epsilon constraint method (Haimes, 1971), exploits the monotonicity of the alternatives' cumulative probabilities in this problem class to offer better computational performance than the SAUGMECON method (Zhang & Reimann, 2014). Motivated by the recognition that implementing portfolios of maintenance actions may take time, we analyze the evolution of consequences associated with decision trajectories, which are defined by the implementation of additional actions. In particular, we extend the concept of first-order stochastic dominance to evaluate decision trajectories and offer guidance for the absolute timing and the relative order of implementing actions. These methodological and computational contributions are illustrated with a realistic asset management problem in the maintenance of network infrastructures.

## 28. The Role of Objective Functions and Solvers in Payload-Dependent Multi-Trip UAV Cargo Routing

Abdullah Tunc Buyuksan<sup>1</sup>, Kerem Utku Demir<sup>2</sup>, Durdu Hakan Utku<sup>1</sup>

<sup>1</sup> University of Turkish Aeronautical Association, Ankara, Turkey

<sup>2</sup> TOBB University of Economics and Technology, Ankara, Turkey

### Abstract | $\Rightarrow$

UAV cargo routing is traditionally formulated as a distance-minimization problem; however, for battery-powered multirotors, mission feasibility and operational efficiency are governed by energy consumption rather than travel distance. Because multirotor power demand depends nonlinearly on instantaneous mass and the vehicle lightens after each delivery, a route's energy cost becomes sensitive to visiting order and payload distribution. The shortest-distance and least-energy routes may therefore diverge. This study quantifies the hidden energy cost of distance-based planning relative to energy-aware planning in a single-depot, battery-constrained, multi-trip problem as a function of total payload and examines the role of algorithm selection in revealing it.

The energy model uses a second-order power function fitted to motor-propeller bench-test data; feasibility, battery capacity, and return-to-depot constraints are evaluated via payload-dependent segment energy. Three metaheuristics are compared: GA+2opt, SA+2opt, and AACO. Payload dependence invalidates constant-time 2opt evaluation, requiring full decoding per candidate. Fixing customer geometry, total payload is varied under homogeneous and heterogeneous distributions. Each instance is solved under both objectives, reporting energy penalty, trip count, and route similarity, along with a sensitivity analysis.

Three findings emerge. First, objectives coincide at low payload ratios but diverge sharply as the ratio rises, especially under heterogeneous loads, showing sawtooth behaviour at trip thresholds with an asymmetric tradeoff. Second, GA+2opt consistently finds the best energy solutions, while SA+2opt lags. Third, AACO, based on distance-driven attractiveness, fails to capture energy divergence even under the energy objective, indicating that savings require both an energy-aware objective and a solver that reflects payload-dependent routing dynamics.

## 29. Connecting Constraint Qualifications, Cycling and Numerical Accuracy in the Outer Approximation algorithm

Erik Tamm<sup>1</sup>, Jan Kronqvist<sup>1</sup>

<sup>1</sup> KTH Royal Institute of Technology, Stockholm, Sweden

### Abstract | $\Rightarrow$

The Outer Approximation algorithm is widely used for solving convex Mixed-Integer Nonlinear Programs. A critical assumption for its convergence is that a constraint qualification must hold when all integer variables are fixed. In practice, this assumption may fail or be nearly violated, for example when Slater's condition is almost not satisfied. Such cases can lead to cycling, which is typically addressed by adding cuts. However, the literature has not examined the scenario where Slater's condition is nearly violated, and the interior of the feasible region is very small.

This work presents new theoretical results that connect the accuracy of the subproblem solution to the occurrence of cycling when Slater's condition is nearly violated. The analysis shows how numerical tolerances in solving the subproblem can influence cycling, even if the constraint qualification is technically satisfied. These results provide a deeper understanding of the conditions under which cycling may arise in practice.

## 30. What's new in SHOT 2.0

Andreas Lundell<sup>1</sup>

<sup>1</sup> Åbo Akademi University, Vaasa, Finland

### Abstract | $\Rightarrow$

The Supporting Hyperplane Optimization Toolkit (SHOT) is an open-source solver for mixed-integer nonlinear programming (MINLP) based on polyhedral outer approximation and primal heuristics. This presentation introduces the major new features of SHOT 2.0, including support for HiGHS as a MIP subsolver, the new SHOTpy Python interface for direct solver interaction, and enhanced callback capabilities for warm-starting, custom primal heuristics, and external cut generation.

## 31. Preconditioned Parallel Solvers for Mean Field Games

Heidi Wolles Ljósheim<sup>1</sup>

<sup>1</sup> The University of Edinburgh, Edinburgh, United Kingdom

**Abstract** |  $\Rightarrow$

We present a scalable optimization framework for solving large-scale variational mean field games using parallel-in-time preconditioning. Our approach applies preconditioners based on temporal parallelism to accelerate the solution of the linear systems arising within the Chambolle–Pock algorithm. Numerical experiments demonstrate faster convergence and strong parallel scalability across a range of benchmark problems, making the method effective for large dynamic optimization problems arising in multi-agent systems, including toy generative models.

## 32. What's new in HiGHS

Julian Hall<sup>1</sup>

<sup>1</sup> University of Edinburgh, Edinburgh, United Kingdom

**Abstract** |  $\Rightarrow$

This talk will give an overview of the latest enhancements, the newest features, and the most recent performance improvements in the HiGHS solvers for LP, QP and MIP. These include a serial variant of the parallel interior point solver, algorithmic enhancements of the PDLP solver, a “Hessian-free” extension to the active-set QP solver, and tuning of the new multi-threaded MIP solver.

### 33. Multi-horizon optimization with embedded neural networks

Michal Kaut<sup>1</sup>

<sup>1</sup> SINTEF, Trondheim, Norway

#### Abstract | $\Rightarrow$

A multi-horizon optimization model with a strategic and operational levels can be interpreted as a an optimization model over the strategic variables, with the operational scenarios forming a function that takes the strategic decisions as an input and returns selected summary statistics. In cases where we have a limited number of strategic variables and a complex, hard-to-solve operational model (for ex. including integer variables), we may consider replacing the whole operational level with trained neural networks embedded in the optimization model. In this talk, we present our experience with this modelling approach.

## 34. ICNN-enhanced 2SP: Leveraging input convex neural networks for solving two-stage stochastic programming

Yu Liu<sup>1</sup>, Fabricio Oliveira<sup>2</sup>, Jan Kronqvist<sup>3</sup>

<sup>1</sup> Aalto University, Espoo, Finland

<sup>2</sup> Technical University of Denmark (DTU), Kgs. Lyngby, Denmark

<sup>3</sup> KTH Royal Institute of Technology, Stockholm, Sweden

### Abstract | $\Rightarrow$

Two-stage stochastic programming (2SP) provides a basic framework for modelling decision-making under uncertainty, yet scalability remains a challenge due to the computational complexity of evaluating the recourse function. Existing learning-based methods, such as Neural Two-Stage Stochastic Programming (Neur2SP), employ neural networks (NNs) as recourse function surrogates but rely on computationally intensive mixedinteger programming (MIP) formulations. We propose ICNN-enhanced 2SP, a method that leverages Input Convex Neural Networks (ICNNs) to exploit linear programming (LP) representability in convex 2SP problems. By architecturally enforcing convexity and enabling exact inference through LP, our approach eliminates the need for integer variables inherent to the conventional MIP-based formulation while retaining an exact embedding of the ICNN surrogate within the 2SP framework. This results in a more computationally efficient alternative, and we show that good solution quality can be maintained. Comprehensive experiments reveal that ICNNs incur only marginally longer training times while achieving validation accuracy on par with their standard NN counterparts. Across benchmark problems, ICNN-enhanced 2SP often exhibits considerably faster solution times than the MIP-based formulations while preserving solution quality, with these advantages becoming significantly more pronounced as problem scale increases. In the most challenging instances, the method achieves speedups of up to 100 *times* and solution quality superior to that of MIP-based formulations.

## 35. Neural Surrogates for Bilevel MIP

Lorenzo Demaria<sup>1</sup>, Axel Kärrholm<sup>1</sup>, Jan Kronqvist<sup>1</sup>, Per Enqvist<sup>1</sup>

<sup>1</sup> KTH, Stockholm, Sweden

### Abstract | $\Rightarrow$

In adversarial sensor placement a leader places sensors anticipating a follower's optimal response. This type of problem is common in infrastructure protection and monitoring applications and often leads to bilevel integer programs. When the inner problem is an integer program, these problems tend to become intractable. This motivates the use of neural surrogates for the inner problem which in turn lets us reformulate the problem as a single level mixed integer program.

In this work we specifically investigate an optimal sensor placement strategy that maximizes a minimal detection path through a monitoring area discretized as a hexagonal grid. The inner program is thus a shortest path problem, which, while being integer, enjoys the property of having a totally unimodular constraint matrix. This lets us solve the problem exactly and use it as a benchmark which is often missing in bilevel applications.

The networks we train to predict the shortest paths are ReLU networks and we embed them exactly into a mixed integer program with big-M formulations where we improve the big-M constraints with optimization based bound tightening. We show how standard metrics, like test-accuracy on the surrogate predictions versus the actual shortest paths correlate poorly with the quality of sensor placements. We characterize this by formulating an optimization problem to find the worst test-prediction error. Furthermore, we evaluate various training techniques like dataset composition and extend the setting to a multiobjective problem, balancing coverage and shortest path cost showing the tradeoffs between the two in a surrogate setting.

## 36. Beyond fully input convex networks: tractable surrogate-based optimisation with the input convex neural network class

Yuanxiang Yang<sup>1,2</sup>, Yu Liu<sup>3</sup>, Claudio Roncoli<sup>1,2</sup>, Fabricio Oliveira<sup>3,4</sup>

<sup>1</sup> Mobility and Industrial Management (MIM), Faculty of Engineering Science, KU Leuven, Leuven, Belgium

<sup>2</sup> Department of Built Environment, Aalto University, Espoo, Finland

<sup>3</sup> Department of Mathematics and Systems Analysis, Aalto University, Espoo, Finland

<sup>4</sup> DTU Management, Technical University of Denmark, Lyngby, Denmark

### Abstract | $\Rightarrow$

Embedding trained neural networks as surrogates for intractable objective or constraint functions has become a powerful paradigm for optimisation problems. Generic feedforward neural networks with ReLU activations admit exact mixed-integer reformulations, yet the associated binary variables render the resulting programs computationally expensive as the network size grows. When the underlying response is approximately convex or concave, input convex neural networks (ICNNs) offer an alternative, but existing analysis has largely centred on fully input convex networks (FICNNs). This work broadens the scope to the wider ICNN class, encompassing FICNNs together with partially input convex networks (PICNNs) and input convex recurrent networks (ICRNNs). We show that each architecture admits an exact linear programming (LP) reformulation via the epigraph that introduces no integer variables, and that this relaxation is tight at optimality under direct minimisation of the surrogate output. The broadened class extends its reach beyond static convex surrogate targets, with PICNNs accommodating auxiliary non-convex features and ICRNNs capturing sequential dependencies, while retaining global optimality and solution efficiency. We illustrate the approach on a real trajectory planning problem in which analytically unavailable safety interactions are replaced by data-driven convex surrogates, yielding programs that solve to global optimality in real time and improve consistently over a simulation baseline. The results indicate that the ICNN class offers a principled and tractable route to embedding learned components in mathematical optimisation whenever the surrogate is convex in the decision variables.

## 37. A Column Generation Methodology for Electric Air Transport Network Design Optimization

Eyrun Aradottir<sup>1,2</sup>, Jonas Westin<sup>3</sup>

<sup>1</sup> Mid Sweden University, Sundsvall, Sweden

<sup>2</sup> The Swedish National Road and Transport Research Institute (VTI), Stockholm, Sweden

<sup>3</sup> Umeå University, Umeå, Sweden

### Abstract | $\Rightarrow$

This study presents a column generation methodology for designing Public Service Obligation (PSO) electric air transport networks using a time-space network formulation. The underlying problem is modelled as a multicommodity flow problem that simultaneously captures passenger assignment and aircraft movements. Because the MILP model becomes computationally expensive as network size increases, an approach based on column generation is applied. This enables the model to handle larger networks that the model is currently not able to solve. Passenger flows are then represented directly on the network, while the aircraft operations are represented through dynamically generated route columns. The method consists of a Restricted Master Problem (RMP) and a Pricing Problem. The RMP optimizes passenger flows and selects feasible aircraft routes while enforcing seat capacity constraints linking passenger demand and aircraft supply. Dual variables associated with capacity constraints provide information on the marginal value of additional seat capacity across the network. The Pricing Problem uses these dual values to generate new aircraft routes with negative reduced cost. Aircraft routing is formulated as a minimum cost routing problem on a network that represents both location and time, where reduced arc costs incorporate operational costs and the shadow value of capacity. Routes are generated iteratively until no additional improving columns can be found. The proposed methodology improves scalability and allows the model to handle larger PSO air transport networks.

## 38. The Primal-Dual Hybrid Gradient Method for Column Generation in Vehicle Routing

Joseph Löfving<sup>1,2,3</sup>, Ann-Brith Strömberg<sup>2,3</sup>

<sup>1</sup> Volvo Group, Gothenburg, Sweden

<sup>2</sup> Chalmers University of Technology, Gothenburg, Sweden

<sup>3</sup> University of Gothenburg, Gothenburg, Sweden

### Abstract | $\Rightarrow$

The Primal-Dual Hybrid Gradient Method (PDHG)—or Chambolle-Pock algorithm—has recently made its way into various linear programming solvers, with its use often motivated by GPU parallelism and low memory usage. In this talk we explore its benefits in the less commonly discussed context of Column Generation.

In Column Generation, one sequentially solves many highly similar linear programs, referred to as restricted master problems (RMPs), with the dual solution to each such RMP affecting the problem-specific so-called “pricing subproblem”. Due to the high similarity from one RMP to the next, warm-starting is beneficial, making the warm-startable Simplex Method the most common linear programming solution method for the RMPs.

In the literature for the Vehicle Routing Problem (VRP), it has been noted that the set covering formulations used when applying Column Generation to VRP are often highly degenerate, leading to multi-dimensional polyhedra of optimal dual solutions. The Simplex Method finds extreme points to these optimal dual polyhedra, which has proven to lead to less useful pricing subproblems than non-extreme point solutions would, requiring more Column Generation iterations overall before convergence. More useful non-extreme dual optima could be obtained using the Interior Point Method (IPM), but IPM cannot be warm-started.

In this talk, we investigate the efficacy of replacing the Simplex Method with PDHG within Column Generation for solving VRPs. Like Simplex, PDHG can be warm-started, and like IPM, PDHG inherently generates the nonextreme solutions one ideally wants when solving VRP using Column Generation, giving a combination of two highly desirable properties.

### 39. Optimizing persistent surveillance missions for UAVs by column generation

William Stenberg<sup>1</sup>, Caroline Granfeldt<sup>2,3</sup>, Torbjörn Larsson<sup>3</sup>, Roghayeh Hajizadeh<sup>3</sup>

<sup>1</sup> Saab AB, Stockholm, Sweden

<sup>2</sup> Saab AB, Linköping, Sweden

<sup>3</sup> Linköping University, Linköping, Sweden

#### Abstract | $\Rightarrow$

This paper explores the use of column generation methods to solve an extended vehicle routing problem tailored to surveillance missions using unmanned aerial vehicles (UAVs). The goal is to minimise the number of UAVs required by finding optimal routes while still meeting surveillance requirements for objects. A mission involves a fixed set of locations that must be persistently monitored and a number of depots from which UAVs can be deployed. The surveillance requirements are defined by specific maximum revisit intervals for the objects, and a single UAV may perform multiple depot tours within a route.

The method used to solve the problem is an extended set-partitioning formulation combined with a column generation problem, which is a resource-constrained, prize-collecting travelling salesman problem. The column generation problem generates tours for each depot and maximum revisit interval configuration, and the setpartitioning model select and combines these tours into routes. Lastly, a post-processing step is used to the obtained solutions to reduce total route times.

To evaluate the model, artificial instances with a varying number of depots and monitoring locations are constructed. The results show that the model can produce near-optimal solutions.

## 40. A Column Generation Approach for Noise-Aware Drone Routing with Operational Costs

Haoye Chen<sup>1</sup>, Jan Kronqvist<sup>1</sup>, Zhenliang Ma<sup>1</sup>

<sup>1</sup> KTH Royal Institute of Technology, Stockholm, Sweden

### Abstract | $\Rightarrow$

With the rapid development of drone technologies, the low-altitude economy has attracted increasing attention. However, limited research has examined how to balance the noise impacts of drone operations with operational efficiency. This paper investigates the noise-aware drone routing problem while accounting for operational costs. We develop a column generation algorithm to minimize the overall cost, which incorporates detour distance, flight attitude, waiting time, collision risk, and marginal noise increase. The proposed algorithm is validated through a case study in Stockholm. The results show that the model can effectively mitigate noise impacts while incurring only acceptable additional operational costs.

## 41. Operational Impacts of Green Fuels on Feeder Liner Shipping

Sara Faugstad Amundsen<sup>1</sup>, Sondre Vangberg<sup>1</sup>, Mohamed Kais Msakni<sup>1</sup>

<sup>1</sup> NTNU, Trondheim, Norway

### Abstract | ⇒

The maritime sector must adopt low- and zero-carbon fuels to meet increasingly stringent decarbonization targets. However, their introduction creates challenges across the industry, from infrastructure investment and vessel design to fleet deployment and daily operations. Compared with conventional marine fuels, alternative fuels are more costly and often set tighter operational constraints resulting from lower energy density, larger storage requirements, and reduced sailing range. These constraints are particularly important in liner shipping, where services are expected to operate on reliable fixed weekly schedules, and in feeder networks, where smaller vessels and limited bunkering infrastructure can make fuel capacity and bunkering access critical for both cost and feasibility.

This presentation discusses how alternative fuels affect the design and operations of feeder liner networks. A two-stage solution approach is developed. In the first stage, a label-setting algorithm generates feasible and non-dominated routes for a specific fuel type, considering cargo demand, vessel sizes, fuel range, and bunkering possibilities. In the second stage, a mixed-integer programming model selects the cost-effective routes for weekly demand at all served ports while considering fuel properties, bunkering plans, and leg-specific sailing speeds. The computational study uses benchmark instances from the literature, covering Norwegian, Baltic, African, and Mediterranean regions, and evaluates several alternative fuels, including methanol, LNG, hydrogen, and ammonia. The results show how fuel choices affect route structures and operational patterns, and point out the importance of bunkering availability and emission taxation for the competitiveness of green fuels.

## 42. Norway's Coastal Express as a green corridor: Optimal power system selection and bunkering infrastructure planning

Kenneth Løvold Rødseth<sup>1</sup>, Andreas Breivik Ormevik<sup>2</sup>, Kjetil Fagerholt<sup>3</sup>

<sup>1</sup> Institute of Transport Economics, Oslo, Norway

<sup>2</sup> Norwegian School of Economics, Bergen, Norway

<sup>3</sup> Norwegian University of Science and Technology, Trondheim, Norway

### Abstract | $\Rightarrow$

The Coastal Express has been an integral part of Norway's maritime sector since 1893. A fleet of 11 RoPax vessels operates the 2,000-kilometer-long route that connects southern and northern Norway, servicing 34 ports daily. Historically viewed as a lifeline for passengers and freight, the Coastal Express is subject to public procurement and regulation.

Perceptions about the societal benefits of the Coastal Express are changing, and the appropriate level of service — e.g., routing and scheduling — is currently debated. At the same time, the Coastal Express is expected to significantly reduce its greenhouse gas emissions in the next tendering period; i.e., from 2030.

Significant research gaps relate to the green transition of the Coastal Express, and its current operators are undertaking uncoordinated investigations into low- and zero-emission vessel concepts. To offer holistic decision support, a Mixed-Integer Programming problem for developing a cost-minimizing bunkering plan for the Coastal Express is proposed herein. Key decisions are power system and bunkering location selection.

A particularly novel feature of our model is its consideration of network externalities. We use Automatic Identification System (AIS) data to identify the potential for the maritime fleet to co-utilize bunkering infrastructures operated by the Coastal Express, hence enabling the comparison of the Coastal Express' optimal bunkering plans with and without internalization of network externalities. Although the Coastal Express' value for freight and passenger transports is highest in northern Norway, a key finding of our study is that its value as a green corridor is more pronounced in southern Norway.

## 43. Adapting Liner Shipping Networks to Seasonal Arctic Route Availability

Gleb Sibul<sup>1</sup>, Mikkel Johansen<sup>2</sup>, David Pisinger<sup>2</sup>, Henrik Andersson<sup>1</sup>, Kjetil Fagerholt<sup>1</sup>

<sup>1</sup> NTNU, Trondheim, Norway

<sup>2</sup> DTU, Copenhagen, Denmark

### Abstract | ⇒

Shorter Arctic routes offer significant opportunities for because of their shorter distances, but their seasonal availability creates uncertainty for long-term network planning. Shipping operators must consider not only the potential economic benefits of using Arctic passages, but also the need to adapt when these routes are unavailable or less reliable. This study examines how liner shipping networks can be planned across seasonal conditions while balancing profitability and service continuity. By comparing alternative winter and summer network designs, the work highlights the trade-offs between taking advantage of shorter routes and maintaining a network structure that remains robust under changing maritime conditions.

## 44. Matheuristic for a Rich Feeder Network Design problem

Anandhu Dileep<sup>1</sup>, Ahmad Hemmati<sup>1</sup>, Rahul Nath<sup>1</sup>, Mohammad Moshref Javadi<sup>2</sup>, Kjetil Fagerholt<sup>3</sup>

<sup>1</sup> University of Bergen, Bergen, Norway

<sup>2</sup> University of Illinois Urbana-Champaign, Champaign, United States

<sup>3</sup> Norwegian University of Science and Technology, Trondheim, Norway

### Abstract | $\Rightarrow$

In this work, we study the feeder network design problem, where the goal is to design a set of connected routes to serve container demands associated with a continental port and several feeder ports in a geographic region. We focus on a two-level network structure comprising routes sailed by large vessels that originate from the continental hubs, called mother routes, and routes sailed by small vessels that originate from some of the intermediate feeder ports visited by the mother routes, called daughter routes.

Compared to previous studies, we introduce several problem features that make the problem more realistic. We make restrictions on the maximum allowed time for the transit of each demand through the network, including waiting times during transshipments with associated holding costs per day per container. We allow varied speeds on each arc in the network and also optimize the fuel costs incurred, which is modelled piecewise. In addition, we also consider a few optional demands among some of the feeder ports, which can be rejected with a penalty per container rejected.

To solve this complex network design problem, we design a matheuristic, which works iteratively by modifying the network of routes and solving a mathematical model for each candidate network, which optimizes all the remaining decisions. The algorithm is shown to match closely with an exact mathematical model designed for small instances of the problem and outperform other algorithms on almost all instances of a restricted version of the problem, which was previously studied.

## 45. Diversification in multi-period portfolio optimization

Homayoun Shaabani<sup>1,2</sup>, Bernard Fortz<sup>2</sup>

<sup>1</sup> Molde University College, Molde, Norway

<sup>2</sup> HEC Liège, Liège, Belgium

### Abstract | $\Rightarrow$

Modern portfolio theory, introduced by Markowitz, seeks to maximize returns while minimizing risk through optimal asset allocation. Diversification reduces risk by spreading investments across multiple assets, sectors, and regions, thereby lowering portfolio volatility and limiting potential losses under uncertainty.

Traditional diversification methods face limitations because asset correlations change over time and risk measures such as Conditional Value at Risk (CVaR) are sensitive to estimation errors. Recent research highlights the need for more accurate CVaR estimation and dynamic multiperiod portfolio models, motivating this study's focus on improving diversification and portfolio performance by adjusting CVaR estimation in each investment period.

Multi-period portfolio optimization is an adaptable approach for constructing optimal portfolios over multiple interconnected time periods, as it better reflects changing market conditions through continuous updates of decisions across a future planning horizon. In this study, we develop a multiperiod portfolio optimization model by considering different scenarios and incorporating the CVaR measure.

## 46. Adaptive Weather Routing for Wind-Propelled Vessels under Forecast Uncertainty

Elise Voje Aabel<sup>1</sup>, Andreas Buer Vase<sup>1</sup>, Martin Augestad<sup>1</sup>, Aurore Wendling<sup>2</sup>, Benjamin Lagemann<sup>2</sup>, Kjetil Fagerholt<sup>1,3</sup> (NTNU), Trondheim, Norway

<sup>1</sup> Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology

<sup>2</sup> Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

<sup>3</sup> SINTEF Ocean, Trondheim, Norway

### Abstract | $\Rightarrow$

Wind propulsion has gained renewed interest as a means of reducing greenhouse gas (GHG) emissions from maritime shipping. Wind propulsion systems (WPS) generate climate-neutral propulsion power from wind, reducing fuel consumption and GHG emissions. However, WPS effectiveness depends strongly on wind conditions encountered during a voyage, which are inherently uncertain, making it difficult to accurately estimate emission reduction potential. This uncertainty also makes weather routing a key factor in maximizing that potential.

We study how the time-energy trade-off for wind-propelled vessels can be estimated more accurately through adaptive and stochastic routing methods. We formulate a bi-objective mathematical model minimizing fuel consumption and voyage duration, representing the trade-off through Pareto-optimal solutions derived by solving a one-to-many shortest path problem over a time-space network. The model is embedded in an adaptive routing framework where the route is re-optimized at fixed intervals using updated forecasts.

We evaluate the framework through a case study comparing adaptive routing against a fixed route calculated a priori from the pre-departure forecast. Several uncertainty-handling methods are tested, including a stochastic programming approach representing scenarios as members of an ensemble weather forecast. Both are benchmarked against a theoretical lower bound assuming perfect weather information.

Results show that adaptive weather routing estimates the time-energy trade-off more accurately for WPS-equipped vessels. Compared to a fixed departure plan, the adaptive strategy on average reduces the gap to the perfect-information lower bound from 13.1% to 7.6%, corresponding to a reduction in excess energy consumption of 20.1 MWh for a North Atlantic crossing.

## 47. Robust Medium-Term Hydropower Production Planning: Affine Decision Rules in a Decorrelated Inflow Basis

Gunnar Lidestam<sup>1</sup>, Nils-Hassan Quttineh<sup>1</sup>, Jan Rolfes<sup>1</sup>

<sup>1</sup> Linköping University, Linköping, Sweden

### Abstract | $\Rightarrow$

Vattenfall AB currently uses deterministic optimization models for planning hydropower production. These models assume perfect foresight of the local inflows to the hydropower system when planning spillage and discharge decisions. However, since future local inflows are in practice uncertain, following production plans given by deterministic models may in practice lead to droughts or flooding of the reservoirs.

We present a tailored method for robustifying medium-term hydropower production planning against future local inflow uncertainty using affine decision rules (ADRs). To efficiently capture spatial and temporal correlations in the local inflows, we transform them into random variables  $\xi$  using principal component analysis (PCA). The transformed components are uncorrelated and have zero mean and unit variance. Thus, no direction in  $\xi$ -space is distinguished from another, and it is enough to specify how far  $\xi$  may deviate from the origin: either componentwise, giving a *box*, or in total, giving a *ball*. We derive the robust counterparts for these two sets, yielding a linear program and a second-order conic program, respectively.

The proposed approach is evaluated in a case study of yearly operation planning of the Lule River hydropower cascade. Together with the deterministic model, the two robust programs are solved iteratively within a shrinking-horizon procedure. The robust formulations are shown to dominate the deterministic model in both respects: they match its revenue with far fewer volume violations and achieve higher revenue (with fewer violations still) than the deterministic program with volume safety buffers. The two uncertainty sets produce schedules of similar quality, but the ball uncertainty set yields considerably shorter runtimes than the box.

## 48. Operational planning of technician assignment and task allocation to vessels for offshore wind farm maintenance under service time uncertainty

Vibeke Hvidegaard Petersen<sup>1</sup>, Magnus Stålhane<sup>1</sup>, Stein Wallace<sup>2</sup>

<sup>1</sup> Norwegian University of Science and Technology (NTNU), Trondheim, Norway

<sup>2</sup> Norwegian School of Economics (NHH), Bergen, Norway

### Abstract | $\Rightarrow$

Offshore wind farms (OWFs) rely on frequent maintenance to ensure reliable electricity production. This work considers the daily operational maintenance planning problem of assigning technicians and allocating tasks across a vessel fleet operating at an OWF.

The problem is complicated by uncertainty in service times. While sensors can detect potential component faults - triggering maintenance tasks - on-site inspections are required to determine whether corrective maintenance is necessary. Consequently, service times may vary depending on inspection outcomes.

We present a two-stage stochastic model capturing the decision structure. The core decisions are the technician assignment and task allocation across the fleet. The vessel routing that is a consequence of these can be formulated as a vehicle routing problem with delivery and pickup (VRPDP) of technicians.

The objective is to minimize overall costs by balancing direct vessel operating costs against downtime costs associated with postponed tasks. Downtime costs reflect lost electricity production due to turbines operating at reduced capacity or being shut down.

First-stage decisions determine the core decisions together with the VRPDP prefix. This prefix corresponds to the initial part of the vessel route, starting at the port and continuing until no additional technician teams can be delivered to the remaining allocated tasks. Second-stage decisions complete the vessel routes based on realized service times.

We use machine learning to predict service time distributions and approximate expected routing costs. These approximations enable the evaluation of first-stage decisions without explicitly solving the full VRPDP for each scenario. Computational results will be presented.

## 49. Timbertrail – a decision support tool for efficient harvest planning

Mikael Rönnqvist<sup>1,2</sup>, Erik Rönnqvist<sup>2</sup>, Patrik Flisberg<sup>2</sup>, Mikael Frisk<sup>2</sup>, David Bredström<sup>2</sup>

<sup>1</sup> Université Laval, Quebec, Canada

<sup>2</sup> Creative Optimization, Stockholm, Sweden

### Abstract | $\Rightarrow$

Detailed planning before forest harvest is important for the harvesting and forwarding work to be efficient and with as little negative impact on the soil as possible. With good planning, the risk of machines damaging the soil in sensitive areas is minimized, while resource utilization increases, and energy consumption decreases. Timbertrail is an advanced decision support system (DSS) that uses high-resolution digital information about soil moisture, slope, forest density and conservation. The output is a proposal, in pre-harvest planning, of the optimal placement of the main extraction trails that the forwarder will use from the place for each log pile to the place for the roadside storage. The large multi-objective network design model is solved fast and finds near-optimal solution in a few seconds, enabling efficient online planning as well as mass testing of large datasets. The quick solution times are possible through very fast and adapted decomposition methods. The DSS developed by Creative Optimization and is currently used by six forest companies and three owner organisations in Sweden, Finland and Norway. The first system was put in operations in 2020. It is used both in pre-planning at offices and in direct operations in harvest machines. There are multiple savings. First, the planning time is reduced considerably. Also, better extraction trails and landings make the operations more efficiently in terms of soil damage, work time and energy consumption, i.e., less CO<sub>2</sub> emissions.

## 50. Electrification of forest logistics

Mikael Rönnqvist<sup>1</sup>, Patrik Flisberg<sup>2</sup>

<sup>1</sup> Université Laval, Quebec, Canada

<sup>2</sup> Creative Optimization, Stockholm, Sweden

### Abstract | $\Rightarrow$

The integration of electrical systems into forest transportation and harvesting technologies presents significant opportunities for reducing environmental impact and improving efficiency. However, the transition from traditional systems to electrified alternatives faces a range of challenges, including technological, economic, and infrastructural barriers. This presentation will explore the key challenges in implementing electrical systems for transport and harvesting applications, focusing on issues such as battery technology, energy storage and consumption, grid connectivity, and scalability. A critical aspect of this transition is the coexistence of electrical and traditional systems, as these technologies will likely operate side by side for the foreseeable future. The session will examine how hybrid systems can be optimized for efficiency and performance during this period of parallel operation. Furthermore, an analysis of new initiatives will be provided, highlighting their potential advantages and drawbacks in comparison to established solutions. Through case studies and realworld examples, attendees will gain insights into the current landscape of electrified transport and harvesting technologies and understand the necessary steps for achieving a sustainable and efficient transition while managing the dual reliance on both systems.

## 51. Dynamic Game-Theoretic Analysis of Strategic Pricing in the Swedish Pulpwood Market

Soleiman Mohammadi Limaei<sup>1</sup>

<sup>1</sup> Mid Sweden University, Sundsvall, Sweden

### Abstract | $\Rightarrow$

This study applied dynamic game theory to analyze strategic pricing behavior in the Swedish pulpwood market, focusing on two dominant regional buyers operating in the North (SCA) and Middle (Holmen). Using inflation-adjusted price data from 1995–2020, an empirically parameterized duopsony model was constructed in which each mill chose between high and low pulpwood prices. The resulting payoff matrix yielded a mixed-strategy Nash equilibrium with equilibrium probabilities of 0.65 (North) and 0.35 (Middle), corresponding to expected profits of 4,515.17 and 5,374.03 million SEK.

To capture adaptive behavior, the model was extended using continuous-time dynamic adjustment equations based on marginal expected profits. The dynamic system exhibited oscillatory trajectories that converged toward the mixed-strategy equilibrium. Stability analysis using the Jacobian matrix showed that both eigenvalues were strictly negative, confirming local asymptotic stability and demonstrating that small deviations in pricing strategies dissipated over time.

The results highlighted that strategic interaction—rather than purely exogenous market forces—played a central role in pulpwood price formation. By combining empirical parameterization, mixed-strategy equilibrium analysis, and dynamic stability assessment, the study provided a rigorous operations-research framework for understanding competitive behavior in natural resource markets. The modeling approach was shown to be broadly applicable to procurement environments characterized by concentrated buyer power, repeated interactions, and incomplete information.

## 52. Bi-objective optimization for dairy farm operations to balance profit and greenhouse gas emissions

Julio Cesar Goetz Gutierrez<sup>1</sup>, Rasmus Bang<sup>2</sup>, Mario Guajardo<sup>1</sup>

<sup>1</sup> NHH Norwegian School of Economics, Bergen, Norway

<sup>2</sup> Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway

### Abstract | $\Rightarrow$

Governments and societies strive to balance food production with environmental goals. In this context, balancing farm-level economic and climate goals is a key goal not only for farmers but also for policymakers and the broader society. This study aims to examine economic performance and greenhouse gas (GHG) emission intensity in combined milk and beef production on dairy farms. We present a bi-objective optimization framework to economically optimize production at farm level under various operational constraints while minimizing the corresponding GHG emissions. We apply this framework in Norway. The optimization results demonstrate that the effectiveness of various measures to increase economic performance and to reduce GHG emissions strongly depends on operational conditions and the GHG emissions intensity measure used. We compare the results using GHG emissions intensity measure and analyze the impact on the managerial insights to support the dairy farmers.

### 53. Tactical offshore personnel transportation planning on the norwegian continental shelf uses optimized models to match weekly transport demand with helicopter fleets

Vladislav Klyuev<sup>1</sup>, Irina Gribkovskaia<sup>1</sup>

<sup>1</sup> Molde University College - Specialized University in Logistics, Molde, Norway

#### Abstract | $\Rightarrow$

Offshore installations on the Norwegian Continental Shelf rely on chartered helicopters to transport workers between a land-based heliport and the corresponding installations. Keeping these flights regular and efficient is essential for uninterrupted operations. This paper addresses the Weekly Flight Program Planning Problem for transporting offshore personnel during a transition from a homogeneous Sikorsky S-92 helicopter fleet to a heterogeneous helicopter fleet that incorporates Leonardo AW189 helicopters.

Weekly Flight Program Planning Problem tackles the tactical planning problem, where a fixed weekly passenger demand must be satisfied by choosing the cost-optimal fleet of helicopters and building a recurring weekly flight timetable. A passenger-based mixed-integer programming formulation is developed, which simultaneously selects helicopter resources and assigns passengers to flights and flights to start times.

A two-stage iterative decomposition algorithm is proposed to cope with the model's high dimensionality. The first stage determines the optimal fleet composition and allocates passenger demand to weekdays flights; the second stage schedules daily flights, utilizing helicopter resources selected in the first stage. If solution infeasibility is detected, helicopter resources are revised exploiting the marginal least-cost increase and the algorithm iterates to the first stage until a feasible least-cost solution is found.

Computational experiments on industrial data are conducted to validate the algorithm and analyze its performance. It is confirmed that cost-optimal weekly flight programs for real-size instances on the NCS can be generated in very short time, providing decision-support tool for tactical helicopter planning with heterogeneous fleet, offering quantitative insight into fleet composition and valuating contractual options.

## 54. Crew Transfer Vessels Routing for Offshore Wind Farm Maintenance: Impacts of Electric Vessel Charging Consideration

Paulo Cesar Ribas<sup>1</sup>, Olivia Caranda<sup>1</sup>

<sup>1</sup> Molde University College, Molde, Norway

### Abstract | $\Rightarrow$

Offshore wind energy has grown rapidly worldwide, increasing the importance of efficient operation and maintenance (O&M) strategies to reduce costs and improve reliability. Crew Transfer Vessels (CTVs) play a critical role in offshore maintenance operations, making routing and scheduling optimization essential for reducing downtime and operational expenses. In addition, the use of electric vessels is a promising approach to reducing carbon emissions.

We have developed an optimization model for CTV routing with multiple vehicles and voyages and applied it to both conventional diesel CTVs and the electric CTV (e-CTV).

The impact of electric Crew Transfer Vessel (e-CTV) charging and battery constraints on the optimal routes is analyzed and discussed.

The model is tested using Dogger Bank A-inspired data under different maintenance scenarios and fleet configurations. The study demonstrates the impact of electric vessel constraints on routing performance and operational efficiency. Overall, this research contributes to the development of more realistic and sustainable offshore maintenance routing strategies for offshore wind farm operations.

## 55. Emissions estimation in offshore logistics planning: insights into Offshore Maritime Logistics Optimisation Workbench

Victoria Gribkovskaia<sup>1</sup>, Yauheni Kisialiou<sup>1</sup>

<sup>1</sup> SINTEF Ocean, Bergen, Norway

### Abstract | $\Rightarrow$

With Norwegian national greenhouse gas intensity regulations confirmed, oil and gas operators on the Norwegian continental shelf will face new requirements and motivation for reducing the footprint from their marine operations based on the used energy carriers starting from year 2029. Now is the time for operators to investigate options for improved energy efficiency from joined operations, improved use of batteryhybrid energy systems, and the introduction of alternative fuels together with other operators and ship owners. We present tactical and operational level supply fleet planning capabilities, and options for emissions estimation with varying degrees of ship and energy system detail, within the Offshore Maritime Logistics Optimisation Workbench developed by SINTEF Ocean.

## 56. Optimizing Battery Utilization in Hybrid Offshore Support Vessels: Evidence from Operational Data

Gabriel Fuentes<sup>1</sup>, Victoria Gribkovskaia<sup>2</sup>, Mario Guajardo<sup>1</sup>

<sup>1</sup> NHH Norwegian School of Economics, Bergen, Norway

<sup>2</sup> SINTEF Ocean, Bergen, Norway

### Abstract | $\Rightarrow$

This study investigates the utilization of Battery Energy Storage Systems (BESS) in hybrid Platform Supply Vessels (PSVs) operating on the Norwegian Continental Shelf. Using one year of high-frequency telemetry data combined with AIS-based operational mode classification, the analysis reveals that batteries are significantly underutilized, with operations concentrated within narrow state-of-charge (SOC) ranges and limited cycling. Building on these findings, two Energy Management System (EMS) strategies are evaluated: a rule-based heuristic and a mixedinteger linear programming (MILP) optimization model. Results show that expanding SOC operating windows improves fuel efficiency, particularly when tailored to operational modes. The rule-based strategy achieves approximately 2.6% fuel savings but introduces frequent genset start–stop cycles, limiting operational feasibility. In contrast, the MILP model optimizes genset loading and battery scheduling, achieving up to 4.5% fuel savings (*approx* 1.1 tonnes) while maintaining stable operations. This study preliminary results signals that larger batteries are required for a meaningful applicability.

## 57. Threshold-Safe Dynamic Release Scheduling under Finite Recovery

Aleksandr Omelchenko<sup>1</sup>

<sup>1</sup> Constructor University Bremen GmbH, Bremen, Germany

### Abstract | $\Rightarrow$

We study a deterministic dynamic optimisation problem for threshold-safe release scheduling under finite recovery. A fixed external load must be absorbed by a recovering system through staged releases. The decision problem is to choose the number, size and timing of releases so that a critical threshold is not exceeded, while accounting for recovery and fixed staging costs.

The motivating application is political shock absorption, but the formulation is not a political forecasting model. The load is treated as given, and the objective is to construct a conservative operational benchmark for safe absorption. The model is derived from a reduced compartmental voter-flow system with a mobilisation variable and a stress reservoir. In the relevant parameter regime, the mainstream baseline is locally attracting below a critical reservoir level and locally amplifying above it. We show that the nonlinear system admits a scalar leakyreservoir impulse envelope, so threshold safety in the scalar model gives a sufficient safety certificate for the underlying compartmental mechanism.

The scalar model yields closed-form optimisation results. Under complete recovery, the exposure-minimising split into a fixed number of releases is uniform, and the minimal threshold-safe number of releases is explicit. With fixed overhead per release, the model gives a setup-cost trade-off between full safety and controlled residual exposure. Under finite recovery, equal splitting is no longer optimal; the peak-minimising policy equalises postrelease reservoir levels, producing a front-loaded loading-plus-maintenance profile. For a fixed horizon, we derive a sharp capacity frontier for threshold-safe absorption.

## 58. Dynamic Offering and Pricing of Mixed Last-Mile Delivery Options via Approximate Dynamic Programming

Ze Zhou<sup>1</sup>, Balázs Kulcsár<sup>1</sup>

<sup>1</sup> Chalmers University of technology, Gothenburg, Sweden

### Abstract | $\Rightarrow$

The growth of e-commerce has intensified the need for last-mile delivery systems that can jointly manage customer choice and operational efficiency. We study the Dynamic Offering and Pricing of Mixed Delivery Options (DOPMDO) problem, in which a logistics service provider dynamically selects and prices attended homedelivery time slots and out-of-home pickup options for sequentially arriving customers. Each decision affects immediate revenue, customer acceptance, and the route-dependent fulfillment cost realized at the end of the booking horizon. We formulate DOPMDO as a finite-horizon Markov decision process and propose State-Value Anchored Pricing via Approximate Dynamic Programming (SVAP-ADP). The method learns a continuation-value approximation on an aggregate state representation of the mixed-delivery system and uses accepted-versusrejected value differences to estimate option-level opportunity costs. These opportunity costs are embedded in an anchored trust-region pricing problem around a calibrated fine-static benchmark. Computational experiments on a real-world Seattle last-mile delivery instance show that SVAP-ADP improves mean profit by approximately \$7.0\%\$ relative to current practice by lowering terminal fulfillment cost while preserving a stable home-locker-opt-out mix. The assortment-control experiments further show that the value of dynamic pricing depends critically on the offered menu: the profit gain is \$14.3\%\$ under a restricted nearest-locker menu, but rises to \$80.2\%\$ when the candidate pool is enriched with operationally valuable locker options. These results indicate that anticipatory pricing and assortment control are complementary: pricing steers customers toward lower-cost options, but the menu determines whether high-value consolidation opportunities are available in the first place.

## 59. Dynamic flow synchronisation of perishable goods

Brede Sørøy<sup>1</sup>

<sup>1</sup> BAMA Gruppen, Oslo, Norway

### Abstract | $\Rightarrow$

BAMA is a Norwegian distributor and wholesaler of fresh produce, sourcing fruit, vegetables, and flowers from both Norwegian and international suppliers. Delivering highly perishable products requires effective synchronisation of transportation, inventory, warehouse operations, and customer deliveries across a complex supply network.

To further improve supply chain performance, BAMA is investigating how optimisation methods can support the planning and synchronisation of inbound and outbound product flows. The problem involves balancing customer demand, transportation activities, inventory availability, and operational resource constraints in an environment characterised by incomplete information and frequent changes.

The planning process must account for decisions that are made before all relevant information is available, while remaining responsive to new information revealed throughout the day. This creates a dynamic optimisation problem in which plans are repeatedly updated as operational conditions evolve. The resulting optimisation problem combines elements of scheduling and flow synchronisation across interconnected logistics processes, where the timing of inbound deliveries directly influences product availability for outbound demand.

A mixedinteger programming model is being developed to support both planning and replanning decisions. The model aims to generate highquality solutions within practical time limits, enabling transportation coordinators to react quickly to changing conditions. As new information becomes available, previously generated plans may need to be revised to maintain an efficient and feasible flow of goods through the supply network.

The presentation discusses the problem context, the modelling approach, and key challenges associated with applying optimisation to dynamic flow synchronisation in the distribution of perishable goods.

## 60. Online Distributed Learning with Sublinear Regret for Virtual Reality Networks

Rebecka Haraldsson<sup>1</sup>, Krishnendu S. Tharakan<sup>1</sup>, Carlo Fischione<sup>1,2,3</sup>

<sup>1</sup> KTH Royal Institute of Technology, Stockholm, Sweden

<sup>2</sup> Digital Futures, Stockholm, Sweden

<sup>3</sup> SweWIN, Stockholm, Sweden

### Abstract | $\Rightarrow$

Edge caching is a key enabler for latency-sensitive applications such as immersive video and virtual reality (VR). However, VR content demand is inherently time-varying due to head movement, user mobility, and scene dynamics, making fixed popularity-based caching policies inadequate. We study distributed online caching for multi-BS VR edge networks, where each base station (BS) observes only local demand and updates its cache allocation sequentially. We formulate the problem as online concave utility maximization over cache-capacity constrained feasible sets, where cache decisions must be made sequentially before the current demand realization is fully known. To solve this problem, we propose a neighbor-aided projected gradient ascent algorithm that preserves feasibility of the cache allocations at every time slot. We derive a dynamic regret bound with respect to the best time-varying feasible allocation in hindsight. The bound decomposes the regret into terms associated with temporal variation of the optimal allocation sequence and cumulative deviation between local and neighborinformed gradient directions. We further introduce a switching-aware regret formulation that penalizes movement between consecutive cache allocations, thereby incorporating replacement costs and connecting the model to online optimization with switching costs. The result shows that the proposed policy achieves sublinear dynamic regret when the optimal cache sequence varies gradually and neighboring gradients remain informative. Simulations using the MUSMET dataset demonstrate improved adaptation to time-varying demand compared with local online caching and popularity-based baselines.

## 61. Operations Research for Tactical Command and Control: An Integrated Decision-Support Pipeline for Course-of-Action Evaluation

Cengizhan Dogan<sup>1</sup>, Tunc Buyuksan<sup>1</sup>, Oguzhan Erdogan<sup>1</sup>

<sup>1</sup> Eper Technologies, Ankara, Turkey

### Abstract | $\Rightarrow$

Tactical command-and-control (C2) staff must evaluate competing courses of action (COAs) under coupled constraints—terrain and weather, enemy threat, expected attrition, and logistic sustainability—a task still performed largely by manual estimation under severe time pressure. We present an integrated operations-research pipeline, implemented in Eper Technologies' SARP decision-support system, that composes several classical OR and decision-analysis methods on a shared geospatial state to rank candidate COAs.

The pipeline combines: (i) a probabilistic threat layer that models weapon engagement zones with distance-decayed hit probability and combines overlapping zones as  $1 - \prod_i (1 - p_i)$ , alongside an electronic-warfare layer derived from a free space path-loss propagation model; (ii) a multi-phase Lanchester attrition model with morale and supply feedback that predicts force-ratio outcomes; (iii) a vehicle-based logistics model forecasting fuel, ammunition, and ration consumption and the sustainability horizon; and (iv) a multi-criteria decision-analysis scorer (the FACES framework—feasibility, acceptability, completeness, distinguishability, suitability) that fuses these engine outputs into a single comparable COA score.

Our contribution is application-oriented: rather than new theory, we show how textbook OR methods integrate, through a shared spatial state and consistent uncertainty handling, into a deployable C2 decision-support tool, and we discuss the modelling choices, couplings, and limitations that arise when classical OR is operated under real tactical workflows.

## 62. Multiobjective Grey-Box Optimization with Applications in the Mining Industry

David A. Liñán<sup>1</sup>, David Ek<sup>2</sup>, Daniel Marjavaara<sup>2</sup>, Anders Forsgren<sup>1</sup>, Jan Kronqvist<sup>1</sup>

<sup>1</sup> KTH - Royal Institute of Technology, Stockholm, Sweden

<sup>2</sup> LKAB, Kiruna, Sweden

### Abstract | $\Rightarrow$

Complex physics-based simulations are performed at LKAB (Kiruna, Sweden) to understand the bottlenecks of iron postprocessing in induration machines where multiple economic, environmental and product quality objectives interact. To optimize these objectives, simulations can be embedded in grey-box optimization models, i.e., models where a process simulator is coupled with an algebraic model. Derivative-free algorithms such as mesh adaptive direct search (MADS) can handle simulation-based optimization problems but do not exploit algebraic structures, e.g., derivatives. Conversely, algebraic modeling environments such as Pyomo provide access to powerful solvers for algebraic optimization but cannot handle black-box components directly.

Motivated by the optimization challenges faced by LKAB, this work introduces a Multiobjective-Hybrid-MADS (MHMADS) algorithm. MHMADS relies on a weighted Tchebycheff single-objective scalarization of the multiobjective problem. Each scalarized problem is solved by Hybrid-MADS (HMADS), which integrates MADS with a cutting-plane search step that exploits model structure by keeping algebraic model components in a cuttingplane Pyomo model. Also, MHMADS implements a history-sharing mechanism: the cutting-plane model and black-box evaluations accumulated during one scalarized subproblem can be carried over as a warm start for the next, reducing black-box evaluation costs. The performance of MHMADS is illustrated through the optimization of an induration system, with the objective of minimizing energy costs while maximizing the internal energy of the iron ore bed. The results show that the cutting-plane search step combined with the history-sharing mechanism reduces the total solving time by around 11 hours of computation compared to a MHMADS baseline without cuts and history-sharing.

## Hexaly: the next-generation MIP solver Abstract | $\Rightarrow$

Mixed-Integer Linear Programming (MIP) has been the dominant optimization framework for decades. While highly successful, many real-world problems remain difficult to express naturally within a purely linear paradigm. Large-scale routing, scheduling, packing, simulation-based optimization, and machine-learning-driven decision problems often require extensive reformulations that can obscure problem structure and limit performance.

Hexaly extends the traditional MIP approach with a richer modeling framework designed to capture optimization problems closer to their original form. In addition to classical algebraic modeling, it introduces native combinatorial constructs such as sets, lists, and intervals, together with nonlinear and black-box optimization capabilities. This allows practitioners to model complex systems, simulations, and predictive models directly, without relying on large reformulations.

At the algorithmic level, Hexaly automatically exploits advanced optimization techniques, including decomposition methods, column generation, branch-price-and-cut, and decision diagrams, making sophisticated solution approaches available out of the box.

In this talk, we will present the principles behind this next-generation MIP approach, illustrate its modeling capabilities on routing, scheduling, and packing applications, and provide an overview of the solver's current performance on selected benchmarks.

## 63. Flexible Electric Vehicle Charging with Karma

Ezzat Elokda<sup>1</sup>, Ruiting Wang<sup>1</sup>, Karl H. Johansson<sup>1</sup>, Angela Fontan<sup>1</sup>

<sup>1</sup> KTH Royal Institute of Technology, Stockholm, Sweden

### Abstract | $\Rightarrow$

Motivated by the need to develop fair and efficient schemes to facilitate the electrification of transport, this paper proposes a non-monetary karma economy for flexible Electric Vehicle (EV) charging, managing the intertemporal allocation of limited power capacity. We consider a charging facility with limited capacity that must schedule arriving EVs to charge in real-time. For this purpose, the facility adopts online karma auctions, in which each EV user is endowed with non-tradable karma tokens, places a karma bid in each time interval it is present in the facility, and capacity is allocated to the highest bidders, who must pay their bids. These payments are subsequently redistributed to the users to form a closed, indefinitely sustainable economy. The main contribution is to extend previous karma Dynamic Population Game (DPG) formulations to this setting which features novel State of Charge (SOC) dynamics and private trip deadlines in addition to urgency. A Stationary Nash Equilibrium (SNE) of the EV charging karma economy is guaranteed to exist, and it is demonstrated to provide pronounced benefits with respect to benchmark scheduling schemes as it balances between meeting deadlines and prioritizing high urgency.

## 64. Integrating Operational Considerations into the Dynamic-Arrival-Routes Framework

Roghayeh Hajizadeh<sup>1</sup>, Tatiana Polishchuk<sup>2</sup>, Elina Rönnberg<sup>1</sup>, Christiane Schmidt<sup>2</sup>

<sup>1</sup> Linköping University, Linköping, Sweden

<sup>2</sup> Linköping University, Norrköping, Sweden

### Abstract | $\Rightarrow$

Dynamic arrival routes (DARs) enable the routing and scheduling of aircraft arriving at an airport. DARs form arrival trees that merge traffic from the entry points of the terminal maneuvering area (TMA) towards the runway over a given time period, while guaranteeing temporal separation and optimal descent profiles for all arriving aircraft. To move DARs closer to operational applicability, we extend the optimization framework in three directions. First, we integrate the impact of atmospheric conditions on aircraft's descent profiles. Second, we account for interactions between arriving and departing traffic. Third, we address the complexity of the resulting arrival trees. Merge points, where entrypoint-runway paths merge along the tree, may vary considerably in the TMA across different time periods, potentially increasing air traffic controller workload. To reduce this complexity, we propose a data-driven approach for selecting a candidate set of merge points and incorporate these restrictions into the optimization model.

Using Stockholm Arlanda airport as a case study, we demonstrate that these operational considerations can be incorporated within the DARs framework while maintaining computational tractability. Our results show that restricting merge points to a carefully selected candidate set can substantially reduce arrival tree complexity while preserving feasibility. Furthermore, the framework can accommodate wind and temperature-dependent descent profiles, highlighting its ability to capture aircraft-specific and traffic-dependent operational factors. Overall, the findings show that DARs can accommodate key operational considerations while balancing environmental performance and controller workload.

## 65. What do delivery drivers know, that optimization algorithms don't?

Sophie Blum<sup>1</sup>, Ahmad Hemmati<sup>1</sup>

<sup>1</sup> University of Bergen, Bergen, Norway

### Abstract | $\Rightarrow$

Optimization algorithms aim to generate the best solution to a given problem and often don't take the gap between optimal solution and solution execution into account. A common example of this can be observed in last-mile delivery routing, where drivers often deviate from the routes planned by a decision-support system. The idea of tacit knowledge in this case assumes, that those deviations follow patterns that can help improve the optimization algorithms creating the routes. Working towards this goal, we use Machine Learning to predict for a given planned route, if a driver is likely to deviate from it. The models are trained on a dataset from a Norwegian logistics company, containing both planned routes and those that driver actually drove. We aim to improve prediction by integrating both road distance and sensible ordering into a new distance deviation measure.

## 66. MILP Formulation for a Rich Multi-Depot Pickup-and-Delivery Problem with Trailer Operations, Driver Regulation, and Equipment Compatibility

Magnus Levinsen<sup>1,2</sup>, Dario Pacino<sup>1</sup>

<sup>1</sup> Technical University of Denmark, Kongens Lyngby, Denmark

<sup>2</sup> DFDS, København Ø, Denmark

### Abstract | $\Rightarrow$

This study addresses a rich Pickup, Delivery, Drop-off, and Collection Problem designed for industrial applications. The setting is related to the practical pickup-and-delivery framework of Xu et al. (2003) but differs in several aspects: we model trailer drop-offs and pickups in addition to standard order flows, we consider a multi-depot setting, and we formulate the solution approach as an exact MILP rather than a heuristic-oriented framework. The resulting model includes multiple depots, driver break regulation, trailer compatibility rules, heterogeneous vehicle types, fleet-sizing constraints, and order precedence constraints.

The model is implemented in Julia and solved with Gurobi. A key design choice is to precompute infeasible arcs before model construction. Because the problem is structurally tight, many arc decisions are infeasible a priori; therefore, only necessary variables are declared. This reduces model size and improves tractability for larger instances. Preliminary tests indicate that the model consistently finds feasible solutions across multiple operational scenarios from a major Nordic logistics and shipping company. Solutions have been validated within internal planning workflows and found operationally consistent.

The study contributes an exact MILP framework for a rich VRP that jointly handles several practically relevant constraints, and shows that heavy precomputation can make exact optimization viable for complex real-world logistics planning.

## 67. Delivery Efficiency in Upright Radiotherapy: Bidirectional Chair Rotation in Upright Static Carbon Arcs

Wouter van Weerelt<sup>1,2</sup>, Sophie Wuyckens<sup>1</sup>, Rasmus Bokrantz<sup>1</sup>, Lars Glimelius<sup>1</sup>, Erik Engwall<sup>1</sup>, Jan Kronqvist<sup>2</sup>

<sup>1</sup> RaySearch Laboratories, Stockholm, Sweden

<sup>2</sup> KTH Royal Institute of Technology, Stockholm, Sweden

### Abstract | $\Rightarrow$

Delivery efficiency in upright radiotherapy can be improved through optimization of the energy layer delivery sequence. Specifically, this study seeks to leverage the rotational freedom of upright radiotherapy to improve delivery efficiency of static carbon arc plans by optimizing the delivery sequence.

Plans for a head-and-neck cancer patient were initialized in RayStation with 15 directions and ~650 energy layers. The plans were subsequently filtered to 15, 9, 5 or 3 directions with, at most, 200 energy layers. Different modes of energy extraction from a carbon synchrotron were considered, presenting path-dependent costs based on changing spill, energy switching and beam switching time. Specifically, energy switches opposing the synchrotron's regular extraction direction incurred a large penalty associated with beam reloading. Two rotational modes for the upright treatment device were considered: bidirectional and unidirectional. Bidirectional rotation allowed the chair to change rotation direction freely, while unidirectional rotation enforced continuous one-way rotation. The resultant asymmetric, dynamic traveling-salesman algorithm was solved with a 3-opt algorithm. To mitigate the effect of local minima, three different path initialization methods were used.

Optimization of the delivery sequence with bidirectional rotation caused back-and-forth rotations between adjacent control points, minimizing energy switches opposite to the synchrotron's extraction direction. Likewise in unidirectional rotation, the resultant sequence sought to minimize instances of beam-reloading and, when possible, overlap beam-reloading with large rotations. Overall, optimization of the energy layer sequence utilizing the full rotational freedom of upright systems may improve delivery efficiency, especially in systems with long beam-reloading times. Funded by EU, GA 101168955.

## 68. Choosing prevention strategies for cardiovascular diseases with the aid of the Saari triangle

Jaakko Hakula<sup>1</sup>

<sup>1</sup> Freelance researcher, Kempele, Finland

### Abstract | $\Rightarrow$

Methods of voting and multi-criteria decision-making (MCDM) in healthcare settings are not consciously applied in Finland. To provoke discussion on the subject matter an example of preventive measures of cardiovascular diseases (CVDs) is presented. Six strategies of CVD prevention are chosen: primordial, primary, secondary, tertiary, quaternary, and NO prevention. Back-up information for DM is based on randomized controlled trials, wide populations studies, clinical experience and political debates. The research question is: "How can the six preventive choices be evaluated to mimic real-world DM using voting methods?"

Voting methods in social choice (SC) theory are applied in the spirit of the Saari triangle. As candidates and voters in SC stand for alternatives and criteria in MCDM, a three-alternative example with six CVD-strategic criteria are presented. Alternatives A, B, and C representing three preventive programmes reside in the vertices of the triangle. The preference profile defined by the comparative weights of the criteria (the votes given) remains fixed. Positional and approval voting methods are applied to rank the alternatives.

Depending on the weights of the criteria and the voting method used outcomes may differ remarkably. Irrational outcomes can also appear. The situation is called method dependency. Thus, the results may describe real-world decision problems. One might think that the relative importance of the six prevention measures should follow the initial preferences. However, paradoxical results pop up both in theory and practice. The complex prevention of CVDs on individual and population level is not an exception.

## 69. A Column Generation Approach for Automated Planning of 3D-Printed Applicators in Skin Brachytherapy

Björn Morén<sup>1</sup>, Frej Alpsten<sup>2,3</sup>, Apostolos Raptis<sup>2</sup>, Michael Gubanski<sup>2,3</sup>, Åsa Carlsson Tedgren<sup>2,3</sup>

<sup>1</sup> Linköping University, Linköping, Sweden

<sup>2</sup> Karolinska University Hospital, Stockholm, Sweden

<sup>3</sup> Karolinska Institute, Stockholm, Sweden

### Abstract | $\Rightarrow$

We study an integrated optimization problem for patient-specific skin brachytherapy, where 3D-printed surface applicators are designed together with feasible catheter trajectories and source dwell times, i.e. durations of a radioactive source along the trajectories. A key difficulty is generating smooth and non-intersecting catheter trajectories that can be combined into a high-quality treatment plan. The aim of such a plan is to irradiate a specified target volume while sparing nearby healthy tissue.

The main contribution is a column-generation framework in which clinically feasible catheter trajectories are generated dynamically. In the master problem, candidate catheter trajectories and associated dwell times are selected to optimize a set of dosimetric criteria. The subproblem generates new trajectories and is modelled as a constrained shortest path problem with forbidden subpaths on an acyclic graph. To speed up an integer programming-based approach, we solve the subproblem with a labelling algorithm that exploits the problem structure.

The method is evaluated on a set of realistic phantom cases for scalp cancer with target volumes of varying sizes and shapes. The generated catheter trajectories were judged clinically feasible by a medical physicist. Using a relaxed model for benchmarking, the resulting designs achieve objective values within 25% of the relaxation bound across the tested cases. In addition, the solutions show favourable clinical evaluation metrics, including adequate target coverage and sparing of healthy tissue.

## 70. Robust Patient Ordering in Shared-beam Ion Radiotherapy

Viktor Wase<sup>1</sup>

<sup>1</sup> Raysearch Labs, Stockholm, Sweden

### Abstract | $\Rightarrow$

Ion radiotherapy clinics typically operate several treatment rooms that share a single radiation beam.

We study how to order patients within each treatment room such that the makespan stays short under realistic delays. We model three rooms with one shared beam. Each treatment session has three phases: setup, irradiation, and teardown. Only irradiation requires the beam.

We generate 1000 random instances of 20 patients per room. Each patient draws a setup time uniformly from 10-20 minutes, an irradiation time from 5-20 minutes, and a teardown time from 5-10 minutes (all integer-valued).

To bias optimize schedules that absorb delays, we add the term  $\sum \varepsilon / (x_i + 1)$  to the objective function, where  $x_i$  are the gaps between consecutive treatment sessions in the same room. This encourages schedules with more evenly spaced sessions. With  $\varepsilon$  small relative to the integer-minute granularity, this is a lexicographic tiebreaker: nominal makespan is never compromised. We optimize using multistart simulated annealing.

We evaluate schedules optimized with and without the secondary objective by replaying them under random perpatient delays. In three experiments, every patient is independently delayed by up to five minutes with probability 10%, 20%, or 50%. The delay occurs in either setup, irradiation or teardown, chosen randomly.

Compared to the nominally optimal schedule, the robust schedule shortens the average perturbed makespan by 3 min 57 s, 4 min 40 s, and 6 min 11 s respectively, and is shorter in 86%, 87%, and 89% of simulated scenarios. This is a modest improvement against the nominal schedules.

## 71. Flexible Capacity Strategies for Resource-Constrained Multi-Project Scheduling

Mohamed Ben Ahmed<sup>1</sup>, Stina Nordland<sup>1</sup>

<sup>1</sup> Molde University College, Molde, Norway

### Abstract | $\Rightarrow$

This study investigates a resource-constrained multi-project scheduling (RCMPSP) problem in a manufacturing environment, motivated by the production planning needs of a Norwegian pump manufacturer. The application includes multiple homogeneous projects, each representing identical product units. Each project consists of several jobs linked by precedence constraints and competing for shared machine resources with time-dependent capacity. The primary objective is to allocate jobs across discrete planning periods to minimize total project tardiness while meeting resource constraints and delivery deadlines.

A set of mixed-integer programming models is developed to represent various flexibility strategies for capacity management. The baseline model captures the standard problem. Three extensions incorporate outsourcing, overtime, and their combined mode. These models enable a systematic evaluation of how alternative capacity expansion mechanisms affect tardiness, resource utilization, and production costs. Computational analysis shows the trade-off between delivery performance and the cost of flexibility, indicating that additional capacity options can eliminate delays but may increase overall production expenses.

To improve computational scalability, a matheuristic based on proximity search is proposed. This approach uses feasible schedules generated by a constructive heuristic and iteratively explores restricted neighborhoods to find improved schedules. The approach offers a promising solution for large-scale industrial applications while preserving the solution quality.

## 72. Order-Book Balancing at Scania: Optimization Support for Production Levelling

Saeed Mohammadi<sup>1</sup>

<sup>1</sup> Scania, Stockholm, Sweden

### Abstract | $\Rightarrow$

Deciding when and where each customer vehicle should be produced is a recurring planning challenge in a global production network. At Scania, this order-book balancing problem concerns the assignment of vehicle orders to production units and production dates, while accounting for available capacity, production constraints, disturbances, and customer commitments. The challenge becomes particularly acute when disruptions such as material shortages, transport changes, geopolitical events, or production stops require large parts of the order book to be replanned daily.

This presentation describes an application-oriented optimization approach developed for Scania's production levelling process. We use Mixed Integer Linear Programming to model key planning decisions and constraints at an appropriate level of abstraction for operational use. The aim is to support planners in finding feasible, robust, and customer-oriented production plans that utilize available capacity across several production units while respecting practical limitations in the production system.

We focus on the industrial problem setting, modelling choices, and lessons learned from applying operations research methods in a complex vehicle-production environment. We discuss how optimization can help structure trade-offs between disturbance handling, capacity utilization, and customer demand, and how such decision support fits into a daily planning process where transparency, flexibility, and trust in the results are essential.

## 73. Optimization approaches for long-term structural and operational planning in integrated steel plants

Carl Haikarainen<sup>1</sup>, Henrik Saxén<sup>1</sup>

<sup>1</sup> Åbo Akademi University, Turku, Finland

### Abstract | $\Rightarrow$

Current steelmaking practices involve considerable greenhouse gas emissions, with most of the emissions stemming from the fundamental chemical reactions involved in the production processes. Considerable reductions in the carbon footprint of steel thus require significant changes in the processes, such as shifting from carbonbased reduction of iron ores in blast furnaces to hydrogenbased reduction in shaft furnaces. Steel plants are highly integrated systems with complex interconnections of material and energy streams, and changing the fundamental processes will require reoptimization of the entire operational structure. System performance in terms of costs and emissions is also highly dependent on local conditions such as raw material costs or emissions from electricity generation. Additionally, the transition of a steel plant may span decades during which system configurations are hybrid combinations of traditional and new production processes, requiring their own operational schemes. The European project AgiFlex aims at developing a multiagentbased framework for building software tools to address these challenges in planning, production and energy management that steel plants are facing. This contribution presents modelling and optimization concepts being developed within the AgiFlex project for longterm planning of a steel plant considering transitioning to less carbonintensive production routes, including an example of a centralized transition optimization approach highlighting some of the modelling challenges and possibilities.

## 74. Integrated Balancing and Scheduling of Mixed-Model Human–Robot Collaborative Assembly Lines with Mobile Workers

Pedram Beldar<sup>1</sup>

<sup>1</sup> Department of Electrical Engineering and Automation, University of Skövde, Skövde, Sweden

### Abstract | $\Rightarrow$

Human–robot collaborative assembly lines bring together the flexibility of human workers and the precision of robots. Most existing studies assume that workers stay fixed at their stations, which limits how realistic the models are. This paper studies an integrated balancing and scheduling problem for mixed-model human–robot collaborative assembly lines, where a limited number of human workers can move between stations while a limited number of robots stay fixed at single stations. Tasks depend on the product model and can be done by either a human or a robot, and the model also allows collaborative tasks that require a human and a robot to work together at the same time. We build a mixed-integer linear programming model that decides task-to-station assignment, resource allocation, robot placement, worker deployment, and task sequencing and timing, with the goal of minimizing the cycle time. The model includes practical features such as worker movement with travel times, a limit of one human task per station at a time, robot non-overlap, and precedence relations enforced through both station order and task start times. We use linearization, symmetry-breaking, and contiguity constraints to keep the model tractable. Computational experiments show how well the model works and measure how worker mobility affects line performance, giving useful insights for designing efficient human–robot assembly systems.

## 75. A time expanded network formulation for planning of air defense missions

Kristoffer Tondel<sup>1</sup>, Ludwig Karlsson<sup>2</sup>

<sup>1</sup> Saab Aeronautics, Linköping, Sweden

<sup>2</sup> Saab Aeronautics, Solna, Sweden

### Abstract | $\Rightarrow$

Mission planning has a central role in all air forces, and a well-constructed mission plan can strengthen the execution of many complex operations. Defensive Counter Air is one of the main capabilities of air forces, but the highly dynamic and reactive nature of defensive operations makes them unpredictable and difficult to plan in advance. Operators are instead often forced to rely on generic rules, training, and instincts, potentially resulting in underutilization of resources. In this, modern planning algorithms could be used to improve the utilization of fighter aircraft systems in defensive scenarios.

In our approach, we have developed a mixed integer programming model based on a time expanded network. This allows us to approximate future target positions at different times in the plan. It builds upon previous work where a time-static vehicle routing problem formulation was used. Initial results show that the new approach provides a better representation of the air defence problem which improves the solutions. The system accomplishes the mission for various problem instances while adapting to the uncertain and quickly changing situation.

## 76. Persistent Scenario Classes for Defense Planning via Formal Concepts and Optimization

Torgeir Aambø<sup>1</sup>, Even Tønnsberg<sup>1</sup>

<sup>1</sup> Norwegian Defence Research Establishment (FFI), Kjeller, Norway

### Abstract | $\Rightarrow$

Defense planners routinely use scenarios to test military capabilities against realistic operational settings. To ensure a comprehensive and holistic assessment of the capabilities, the portfolio of scenarios should be broad enough to capture operational requirements that sufficiently model the whole space of possibilities. To construct this space, defense planners often use General Morphological Analysis (GMA), an analytical method developed to understand the solution space of un-quantifiable, complex, multi-dimensional problems. After such an analysis, the resulting possible defense problems are often grouped and aggregated by similarity into scenario classes. This process is currently done manually, which puts several limitations on the methodology, like requiring small and manageable solution spaces, and lacking reproducibility between analysts.

This project introduces a mathematical framework aimed at deriving analytically meaningful scenario classes from morphological solution spaces. The method is general and works for any GMA model. It is based on formal concepts and abstraction graphs, which form the foundation for a class selection process using simple optimization and a persistence lifetime analysis across portfolio sizes.

The result is a simplified, reproducible and iterative approach to scenario classes — and more generally to typologies of structured solution spaces — which still retains room for the expert judgement. We demonstrate the method through examples from Norwegian defense planning.

## 77. An illustrative instance of an Artificial Intelligence Planning Problem formulated as an Integer Problem

Vortechz Andreas Andersson<sup>1</sup>

<sup>1</sup> Vortechz AB, Norrköping, Sweden

### Abstract | $\Rightarrow$

In the research field of Artificial Intelligence, the discipline of planning is a well investigated topic. Some spatialoriented planning problems can be re-formulated as integer programming problems in corresponding metric spaces and one illustrative example based on a puzzle game will be demonstrated, where the resemblance to an Operation Analysis problem instance will be indicated. The principles used may be relevant for the development of Artificial General Intelligence (by imitating neurophysiological systems), as there is established research which shows that there are fundamental principles of cognition for spatial location processing across a number of different species.

## 78. Neural Networks as Mixed Integer Programs: Formulations and Use Cases

Johanna Skåntorp<sup>1</sup>

<sup>1</sup> KTH, Stockholm, Sweden

### Abstract | $\Rightarrow$

Many widely used deep neural network (NN) architectures can be represented exactly as mixed-integer linear programs (MILPs). This connection creates opportunities to apply tools from mathematical optimization to analyze neural networks and the larger systems in which they are embedded. Optimization-based reformulations enable rigorous reasoning about network behavior. One prominent application is neural network verification, where MILP and branch-and-bound methods can provide formal guarantees of robustness and safety. Recent advances, including bound-propagation techniques such as  $\beta$ -CROWN, have significantly improved the scalability of verification by combining strong relaxations with efficient search procedures. At the same time, the size and complexity of modern neural networks make the construction of tight and computationally tractable formulations a continuing challenge. These challenges become even more pronounced when neural networks are incorporated into larger optimization, control, or dynamical systems. In such settings, the quality of relaxations directly impacts both computational performance and the strength of the resulting guarantees, while real-time requirements often impose strict limits on solution times.

This talk provides an introduction to MILP reformulations of neural networks as well as formulations and relaxation techniques that arise in practice. Particular attention will be given to the trade-offs between formulation strength and computational cost, highlighting when different approaches may be most effective. The aim is to provide a broad overview of the growing interface between deep learning, mixed-integer optimization, and dynamical systems.

## 79. Operationalizing a Prospective Assessment Framework for Regional CCS Value Chain Planning under Uncertainty

Volodymyr Kartashov<sup>1</sup>, Irina Gribkovskaia<sup>1</sup>

<sup>1</sup> Molde University College, Molde, Norway

### Abstract | $\Rightarrow$

Industrial regions face increasing pressure to reduce carbon dioxide emissions while maintaining economic activity in hard-to-abate sectors. Carbon capture and storage (CCS) is a relevant mitigation option, but regional CCS deployment depends on coordinated decisions across emission sources, transport infrastructure, storage access, technology costs, environmental performance, policy conditions, and stakeholder participation. These decisions are further complicated by uncertainty regarding future carbon prices, infrastructure availability, technology development, and public-private cooperation.

This paper proposes a prospective framework for regional CCS value chain planning under uncertainty. The aim is to operationalize conceptual CCS assessment principles into a modular decision-support structure that can generate and evaluate alternative regional CCS configurations. The proposed framework integrates capture, transport, storage, techno-economic assessment, life cycle environmental assessment, social welfare considerations, and scenario-based uncertainty analysis. Rather than treating CCS as an isolated plant-level technology, the framework represents it as a regional system shaped by infrastructure choices, policy conditions, and coordination among industrial actors.

The framework is developed as part of a PhD project on regional CCS planning in Møre og Romsdal county, Norway. The regional case provides an empirical context for defining system boundaries, data requirements, uncertainty dimensions, and evaluation criteria. The expected contribution is twofold: methodologically, the paper provides a structured pathway from conceptual prospective assessment to operational regional decision support; practically, it supports more transparent comparison of CCS pathways for regional planning, infrastructure prioritization, and policy development.

## 80. Can less efficient turbines be used to improve wind farms?

Martin Dragseth Gregusson<sup>1</sup>, Ahmad Hemmati<sup>1</sup>, Rahul Nath<sup>1</sup>

<sup>1</sup> University of Bergen, Bergen, Norway

### Abstract | $\Rightarrow$

Wake effects, where downstream turbines in a wind farm experience lower wind speeds, can account for a power loss of over 15%. This paper aims to investigate whether a non-uniform three-dimensional wind farm design can mitigate the this effect. We employ a metaheuristic approach to optimize turbine selection, placement, and height, aiming to minimize the Levelized Cost Of Energy of offshore wind farms. Modeling is conducted in Python using the PyWake library, with simulations performed under both uniform wind conditions and realistic wind data from NORA3, the Norwegian Hindcast Archive.