Final report
2017-018 AVER - Assisted Vessel Recovery

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Background

According to Notteboom [7] approximately 70–80% of vessel round trips experience delays in at least one port. The common causes are bad weather, strikes in ports, congestions in passageways and ports, and mechanical failures. The goal of the AVER project was to develop a series of decision support tools, that within a geographically defined space and a given time-frame will be able to resolve the disruption by getting the vessels back on schedule and the cargo rerouted while minimizing the cost and customer impact. Previously, when a disruption occurs, the operator at the shipping companies manually decides what action to take. For a single delayed vessel a simple approach could be to speed up, but this may be an expensive solution due to increased fuel consumption, and the vessel can still arrive late for connections. It is therefore important to take a holistic approach, where the delayed vessel, connecting vessels, and cargo is taken into account. A simple prototype was developed by Brouer et al. [1] showing that substantial savings can be achieved, but the prototype did not re-route the individual containers to their end destination. The goal of AVER is to assist a detailed planning, that maximizes customer timeliness while keeping operational expenses at a minimum.



Suez Canal blocked by huge container ship (The economist, March 27, 2021)

The project started November 2017. The scientific team consisted of PostDoc David Franz Koza and Professor David Pisinger from DTU. Moreover, a number of people from Maersk Line participated in the project, including Grzegorz Siekaniec, Karina Kjeldsen, Emil Sokoler and Stefan Guericke. In the fall 2019, David Franz Koza was on partial parental leave, so the project was extended. In the fall 2020 and spring 2021 research assistant Rebekka Vaarum Woldseth conducted the last experiments and helped writing the final research paper.

Aim and goal

As part of the digitization strategy Maersk Line is focusing on producing a system consisting of multiple tools that will support the Maersk Line operations. At the heart of the system is an optimization

engine and a routing application, allowing Maersk Line to optimize the actual cargo flows on the actual vessel schedules. This will be used for all cargoes to ensure the optimal routing is applied to the cargo both from a customer and Maersk Line perspective. In addition, it will be used in case of disruptions to vessels or ports by ensuring that the cargo is routed in the most cost effective way while taking into account the different customer segments' needs and requirements. The optimization engine and routing application will be based on an existing system which flows the forecasted cargo on the proforma vessel schedules thereby giving a strategic view of how the cargo will flow in the future. For both versions of the optimization engine and routing application the vessel schedules have to be externally given. This means that in case of a disruption, the user will have to provide scenarios in terms of vessel schedules for the system to evaluate. Hence the vessel recovery scenarios suggested will still be limited by the user's knowledge and experience and the system will thus not be able to harness the full cost saving available.

The AVER project is expected to fill the gap by providing a series of algorithms that within a geographically defined space and a given time-frame will be able to resolve the disruption by getting the vessels back on schedule and the cargo rerouted while minimizing the cost and customer impact. The concept is that all vessels within the geographical area can have their schedules altered as long as they are back on schedule by the end of the given time-frame. In addition, all cargoes need to have a confirmed plan for delivery to the final destination that to the largest extend possible adhere to the promise made to the customer initially.

Changes to a vessel schedule can include changes in speed, omitting one or multiple ports and inducing one or multiple ports and any combination of these. When a disruption affects multiple vessels, the number of possible combinations quickly becomes unmanageable for the human brain. Therefore the saving is expected to be especially high in areas where there is a large number of vessels and ports within a smaller geographical area.

Process

Several meetings with Maersk Line have been held to properly scope the project. All major stakeholders participated in these initial meetings, including network planners, software developers and marine operators, who handle disruptions on a daily basis. Expectations and requirements from all participators were discussed and collected. It was decided to start the project by implementing the model and algorithm published in Brouer et al. [1]. The model was then gradually extended to handle more requirements and constraints. These include, for example, the re-routing of cargo, the generation of multiple alternative solutions or the consideration of potential customer churn.

To test and verify the implemented model, a number of test cases was needed. Maersk marine operators generated realistic test cases to evaluate the developed models and methods. As a valuable outcome of those evaluations, it became evident that alternative solution methods (heuristics) are needed to generate good solutions in a reasonable amount of time for large disruption scenarios.

Scientific results

The work has followed three main directions as outlined below:

- **Recovery planning:**
  In case of a disruption it is necessary to create a recovery plan for the delayed vessel and the vessels it interacts with through planned transshipments of containers.

In [4, 5, 9] an integrated model and solution algorithm for vessel recovery planning is presented, that does not only propose a recovery plan for affected vessels, but also considers the (re)routing of affected cargo to mitigate delayed cargo delivery. The objective function considers both, operational expenses including fuel costs, port call costs and transshipment costs, as well as intangible costs for a negatively affected customer service level due to delays in delivery. Several recovery operations are considered, including: speed-up of vessels, omitting ports, and swapping port calls and the rerouting of affected cargo. Computational experiments are reported for several real-life cases of realistic size, and it is demonstrated that the integrated model in some cases finds a structurally completely different vessel-rerouting as opposed to a two-stage approach.

In [3] uncertainties in recovery planning are studied. Resolving disruptions is a trade-off between minimizing operational vessel costs and port call costs on one side, and minimizing the impact on cargo, such as delays and re-routings, on the other side. One difficulty of finding a good trade-off arises from the fact that cargo related costs are largely not tangible or directly quantifiable, such as lost reputation and customer churn. Incomplete information during the planning of recovery plans adds another challenge: ports may reject a revised vessel schedule if no berthing window is available, resulting in multiple iterations of recovery planning. We present a model and solution method that generates a set of recovery plans for the decision maker.

Finally, [11, 12] study the the multi-commodity network flow problem with soft transit time constraints. This is an essential sub-problem when re-routing containers during disruptions.

- **Integrated berth scheduling and labor ordering:**
  The MSc thesis [10] studies operational berth scheduling and labor ordering for liner vessels. An Integer Programming model is proposed which provides an optimal vessel arrival time and departure time at a single port together with the sailing speed to and from the port. In addition, the model provides an optimal labor ordering for the workers performing container loading and unloading operations. The objective of the model is to minimize the bunker fuel cost for the sailing legs to and from the port as well as the labor-related costs at the port. The model considers tidal restriction constraints and various operational labor constraints.

- **Proactive robustness:** To supplement the reactive recovery planning, some studies have been carried out to construct more robust schedules in liner shipping. The paper [6] studies integrated liner shipping network design and scheduling, while [2] study the transit time constrained fixed charge multi-commodity network design problem. Both of the problems take time constraints into account when designing liner shipping networks.

Practical results

Several of the academic results in AVER have inspired the optimization tool at Maersk. Furthermore, software developers at Maersk have developed a prototype of a user interface for AVER as a tool, and marine operators at different operations centers have started testing the tool, which represented a major milestone in the project. The sourcing of live-data has given access to real disruption scenario data, which we have used to refine the model: to improve solution quality, but also to provide solutions that are easy to implement from an operational perspective.

In order to make AVER applicable in practice, it is however also necessary to

- Refine the models to allow users to have more influence on the generated recovery plans, e.g.: (1) Refined conditions for re-routing cargo, for example: the first discharge port call of cargo should not be changed if the containers are already on board a vessel at the moment the disruption is being resolved. (2) Limitations on how much a planned vessel route can change, for example: a maximum number of allowed port call omissions per vessel.
- Integration of the tool with other Maersk tools, and sourcing of live-data.
- Testing of the tool by marine operators at different operations centers.
- Learning from the user feedback.
- Implementation and testing of more sophisticated algorithms to obtain recovery plans in shorter time.

Collaboration with other maritime projects

The AVER project had a close collaboration with the FUTUREFEED project (also supported by DMF). Monthly meetings were held to discuss ideas and share knowledge, and the collaboration resulted in a number of co-authored papers.

Furthermore, joint seminars were held with other maritime projects, e.g. the umbrella project "Maritime DTU, Forskningsbaseret maritim rådgivning 2019–2020", supported by DMF.

Dissemination

The project has resulted in a large number of journal papers and conference presentations.

The papers [2, 6, 12] have been published in leading ISI journals, including *Transportation Science*, *Transportation Research Part-E* and *Computers & Operations Research*. Furthermore, [3, 4, 9, 11] have been presented at leading international conferences, like *EURO-2019*, *EWGT-2020* and *AIRO Young 2020*.

Finally, David Pisinger was plenary speaker at EURO/ALIO International conference 2018, in Bologna 25-27 June 2018. The title of the talk was *Green Liner Shipping with Optimization* with focus on robust scheduling.

Impact on teaching

Two MSc projects have been supervised as part of AVER. The thesis [8] received the DORS-prize in 2018 for best master thesis in Operations Research.

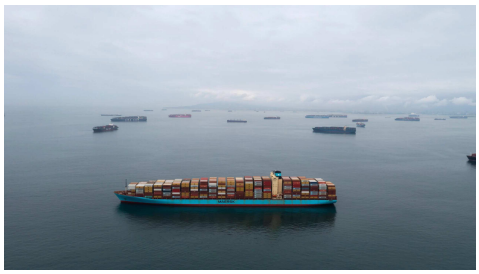
The MSc project [8] studies the Vessel Schedule Recovery Problem. A model based on [1] was implemented and tested on four concrete cases provided by Maersk Line. The results prove satisfactory as they provide solutions at least as good as the real-life decisions made and within reasonable time. Furthermore, a more advanced model is proposed which includes cargo rerouting. The integrated model is able to propose better recovery plans, and is able to propose alternative routes for containers. However, the complexity of the model (and thus the computation times) are significantly increased.

The MSc project [10] worked on a project related to AVER. The project aimed at developing algorithms to facilitate the scheduling and labor ordering for vessels calling US American ports. It

is a frequent operational problem that arises whenever a vessel calls a port in the US, where it is the vessel operator that has to order gangs to load and unload containers from the vessel. The outcome of the master thesis project is very promising, and shows potential savings that can be achieved in using algorithms to plan the gang labor at US ports. Maersk is evaluating whether the savings are worth the development of a tool/software that can be used by the planners.

Finally, results from the project have been used as inspiration for the main project assignment at course *42115 Network Optimization*. The course is annually followed by 150 students at DTU. In the project assignment the students learn to design a cost-efficient liner shipping network, to find cheapest routes for containers, and to reposition empty containers to match demand.

Conclusion and further work



Record number of giant ships are waiting off California. (Popular Science, September 2021)

The COVID-19 crisis has shown how fragile global liner shipping is if one or more ports shut down. This underlines the need for efficient vessel recovery planning tools ,that can support marine operators in planning.

The AVER research collaboration has resulted in a sophisticated, state-of-the art optimization tool that has been implemented and is being tested in a large container liner shipping company; it represents a successful example of applied research that has resulted in an actual product – in this case an in-house tool at Maersk. Within the company, the tool is being integrated with other IT tools that help marine operators to automate and improve their planning.

After AVER, it is planned that Maersk will further develop and extend the tool. Whereas the basic foundation of the project is set and finalized, the testing phase with marine operators is revealing other features that would create additional value for the users and facilitate their daily work.

Future challenges include developing tools for integrated port operations and shipping recovery planning. Also, considering multi-modal transportation, covering the whole supply chain of transportation, may lead to more green and robust solutions.

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[12] Alessio Trivella, Francesco Corman, David Franz Koza, and David Pisinger. The multi-commodity network flow problem with soft transit time constraints: Application to liner shipping. *Transportation Research Part E: Logistics and Transportation Review*, 150:102342, 2021.

Summary of papers and conference presentations

Vessel Recovery with Integrated Container Rerouting
David Franz Koza, David Pisinger, Rebekka Vaarum Woldseth
Technical Report, DTU Management, Technical University of Denmark, 2021

Abstract
Liner shipping services operate at a regular frequency, following published schedules. In practice, however, disruptions to the schedules are quite common and result in late arrivals at ports and thus delayed cargo delivery. Throughout 2020, average global schedule reliability of cargo carriers ranged between 34.3% and 70.3%. Disruptions may occur for many different reasons, such as port congestion, bad weather, mechanical failures or strikes.

In case of a disruption it is necessary to create a recovery plan for the delayed vessel and the vessels it interacts with through planned transshipments of containers. We present an integrated model and solution algorithm for vessel recovery planning that does not only propose a recovery plan for affected vessels, but also considers the (re)routing of affected cargo to mitigate delayed cargo delivery. The objective function considers both, operational expenses including fuel costs, port call costs and transshipment costs, as well as intangible costs for a negatively affected customer service level due to delays in delivery. Several recovery operations are considered, including: speed-up of vessels, omitting ports, and swapping port calls and the rerouting of affected cargo.

The model makes use of a time-space graph formulation of the vessels and containers, resulting in a MIP model based on a path-formulation of the container routes and an edge-formulation of the vessel routes. Advanced pre-processing techniques are furthermore presented to substantially decrease the size of the underlying graph.

Computational experiments are reported for seven real-life cases of realistic size. It is demonstrated that all the instances can be solved to optimality or near-optimality within one hour, and that the integrated model in some cases finds a structurally completely different vessel-rerouting as opposed to a two-stage approach.

Liner shipping disruption management in practice: Generating recovery plans for vessels and cargo
David Franz Koza, David Pisinger, Grzegorz Siekaniec, Emil Sokoler
9th International Conference on Logistics and Maritime Systems
2019

Abstract
In large liner shipping networks, several hundred container vessels operate 24/7, following planned routes and timetables. These networks constantly face unexpected disruptions of varying magnitude. Among the most common reasons are bad weather, port congestions, labour strikes or equipment breakdowns at ports or on vessels. Disruptions may result in delayed vessels, temporarily disabled vessels, reduced port productivity, and port closures. Due to the cargo-driven connectivity of liner shipping networks, even a single delayed vessel can create ripple effects that affect multiple other vessels. Resolving disruptions is a trade-off between minimizing operational vessel costs and port call costs on one side, and minimizing the impact on cargo, such as delays and re-routings, on the other side. One difficulty of finding a good trade-off arises from the fact that cargo related costs are largely not tangible or directly quantifiable, such as lost reputation and customer churn. Incomplete information during the planning of recovery plans adds another challenge: ports may reject a revised vessel schedule if no berthing window is available, resulting in multiple iterations of recovery planning. We present a model and solution method that generates a set of recovery plans for the decision maker. We present preliminary results for test cases that were developed together with our industrial collaborator Maersk.

An integrated vessel schedule and aggregated cargo route recovery model
Grzegorz Siekaniec, David Franz Koza, David Pisinger, Leo Emil Sokoler
30th European Conference On Operational Research, Dublin, Ireland
2019

Abstract
Despite a precisely established plan, disruptions are a reality in liner shipping. They are caused by unforeseen factors such as weather, port congestion, low terminal productivity, crane breakdowns etc. Disruptions vary in magnitude. Smaller disruptions, such as the temporary stop of a crane operations due to fog, often impacts only a single vessel. In contrast, the

closure of a hub terminal as Algeciras for two days due to rough weather in Gibraltar Straits has severe ripple effects that spread across the entire network. Recovery actions for such major events require rescheduling of multiple vessels, as well as cargo re-routing. Maersk, in cooperation with the Technical University of Denmark, is working on a decision support tool aimed at recovering operations after disruptions of different sizes in near real time. The tool uses an integrated approach that jointly optimizes vessel schedules and cargo routes. The objective is to minimize (a) operational cost, mainly vessel related such as fuel and port stays, and (b) impact on cargo delivery dates. The outcome is "cargo-friendly" revised vessel schedules that recovers operations within a fixed time horizon. The practical considerations and mathematical formulation of the model(s) will be presented together with preliminary computational results.

Disruptions in large container shipping networks: How Operations Research can help to get container vessels back on schedule and minimize impact on cargo
David Franz Koza, David Pisinger, Grzegorz Siekaniec, Emil Sokoler
4th AIRO Young Workshop: New Advances in Optimization, Machine Learning and Data Science
2020

Abstract
In large liner shipping networks, several hundred container vessels operate 24/7, following planned routes and timetables. These networks constantly face unexpected disruptions of varying magnitude. Among the most common reasons are bad weather, port congestions, labour strikes or equipment breakdowns at ports or on vessels. Disruptions may result in delayed vessels, temporarily disabled vessels, reduced port productivity, and port closures. Due to the cargo-driven connectivity of liner shipping networks, even a single delayed vessel can create ripple effects that affect multiple other vessels. Resolving disruptions is a trade-off between minimizing operational vessel costs and port call costs on one side, and minimizing the impact on cargo, such as delays andre-routings, on the other side. We present a model and solution method that generates a set of recovery plans for the decision maker. We present preliminary results for testcases that were developed together with our industrial collaborator Mærsk. We will further discuss various challenges that arise in practice-such as incomplete information and intangible costs-and how we deal with those.

Disruption management in liner shipping — Handling vessel and cargo rerouting
Alexandre Orhan, Florian Binter
MSc Thesis, DTU Management, Technical University of Denmark
2018

Abstract
This project presents mathematical models to help liner shipping companies to recover from disruption events. There is disruption when one or several vessels get delayed resulting into significant deviations from the operational planning. More vessels might be impacted due to ripple effects, and on-time delivery of cargo be threatened. However, liner shipping companies are committed to reliability, and must therefore take action to limit the damages. There are several recovery actions and it might be complex to identify in a short period of time the best decision to take given the complexity of the network. This is where Operations Research comes in. Modelling mathematically the network and the potential recovery actions enable the decision-maker to rely on an objective and mathematical tool giving quick results.

The first model investigated is known as the Vessel Schedule Recovery Problem (VSRP) and has been introduced by Brouer et al. (2013). A model inspired from this work has been implemented and tested on four concrete cases provided by Maersk Line. The results prove satisfactory as they provide solutions at least as good as the real-life decisions made and within reasonable time. The model holds promise for helping as a decision-support tool. However, it does not handle container flows but only identify cargo as either delivered on-time, delayed or miss-connected.

Therefore, a more advanced model is proposed which includes cargo rerouting: in the Integrated Recovery Problem (IRP), containers are also capable of flowing through the network, and they can reach their destination using alternative routes instead of being merely considered as miss-connected. After a comparison between the two models, the IRP is shown to present better results and to be able to propose alternative routes for containers when the operational planning is questioned. However, the downside is that it increases a lot the complexity of the model and thus the computation times. A solution would then be to rely on column generation to still generate optimal solutions within reasonable time.

Optimization of Operational Berth Scheduling and Labor Ordering For Liner Vessels
Hildur Sigurjónsdóttir
MSc Thesis, DTU Management, Technical University of Denmark
2019

Abstract
This thesis studies operational berth scheduling and labor ordering for liner vessels. An Integer Programming model is proposed which provides an optimal vessel arrival time and departure time at a single port together with the sailing speed to and from the port. In addition, the model provides an optimal labor ordering for the workers performing container loading and unloading operations. The objective of the model is to minimize the bunker fuel cost for the sailing legs to and from the port as well as the labor-related costs at the port. The model considers tidal restriction constraints and various operational labor constraints. Computational experiments are conducted based on a case study. Furthermore, an extension to the model is proposed, the extended model considers a sequence of ports instead of a single port. For the extended model, a dynamic programming solution approach is suggested and the problem is solved as a shortest path problem

The multi-commodity network flow problem with soft transit time constraints
Alessio Trivella, Francesco Corman, David F Koza, David Pisinger
23rd EURO Working Group on Transportation Meeting (EWGT 2020)
2020

Abstract
The multi-commodity network flow problem (MCNF) consists in routing a set of commodities through a capacitated network at minimum cost and has relevant applications that include routing cargo in railway and liner shipping networks. The standard MCNF does not consider the transit time of commodities, although this is often a critical factor in practical contexts. The literature has therefore introduced hard limits on commodity transit times, which, however, may fail to provide sufficient flexibility since routes with even small delays would be discarded. Motivated by a major liner-shipping operator, we study a generalization of the MCNF in which transit times are modeled as soft constraints and delays are permitted but discouraged using a penalty function of transit time. Similarly, early commodity arrivals can receive a discount. We propose an extension to both arc and path formulations of the MCNF to account for soft transit time constraints. To solve the two formulations we outline, respectively, a new preprocessing technique of feasible transit time durations to reduce the model size, and a column generation method where the subproblem is modeled as a resource-constrained shortest path variant. Extensive numerical experiments conducted using realistic liner shipping instances show that accounting for soft transit time constraints can lead to large savings and that our column generation approach can solve large instances to optimality within a few seconds.

The transit time constrained fixed charge multi-commodity network design problem
Erik Hellsten, David Franz Koza, Ivan Contreras, Jean-François Cordeau, David Pisinger
Computers & Operations Research
Volume 136, Pages 105511, 2021

Abstract
This paper introduces the transit time constrained fixed charge multi-commodity network design problem. Transit times are origin-to-destination time limits for the commodities, which appear for example in transport systems with perishable goods. We discuss how to model the problem and present three different formulations of it. The first formulation is an exponential size path formulation, which we solve with a branch-and-price algorithm. Several speed up techniques from the literature on fixed charge multi-commodity network design problems are implemented, such as lifted cover inequalities and the recently proposed deep dual-optimal inequalities. In an extensive set of computational experiments, we show that these inequalities significantly improve the performance of the algorithm. The other two formulations are of polynomial size: one uses path indices and the other uses time indices. While the branch-and-price algorithm outperforms solving the compact formulations with a general-purpose mixed-integer programming solver, the study of compact models helps better understand the problem, and we can use them as benchmarks. A detailed sensitivity analysis of the branch-and-price algorithm shows that longer transit times and an increased ratio of fixed charge to flow cost increase the difficulty of solving the problem whereas the arc capacity has less impact. We further discuss in-depth implementational details.

The multi-commodity network flow problem with soft transit time constraints: Application to liner shipping
Alessio Trivella, Francesco Corman, David F Koza, David Pisinger
Transportation Research Part E: Logistics and Transportation Review
Volume 150, June 2021, Pages 102342

Abstract
The multi-commodity network flow problem (MCNF) consists in routing a set of commodities through a capacitated network at minimum cost and is relevant for routing containers in liner shipping networks. As commodity transit times are often a critical factor, the literature has introduced hard limits on commodity transit times. In practical contexts, however, these hard limits may fail to provide sufficient flexibility since routes with even tiny delays would be discarded. Motivated by a major liner shipping operator, we study an MCNF generalization where transit time restrictions are modeled as soft constraints, in which delays are discouraged using penalty functions of transit time. Similarly, early commodity arrivals can receive a discount in cost. We derive properties that distinguish this model from other MCNF variants and adapt a column generation procedure to efficiently solve it. Extensive numerical experiments conducted on realistic liner shipping instances reveal that the explicit consideration of penalty functions can lead to significant cost reductions compared to hard transit time deadlines. Moreover, the penalties can be used to steer the flow towards slower or faster configurations, resulting in a potential increase in operational costs, which generates a trade-off that we quantify under varying penalty functions.

Deep Dual-Optimal Inequalities for Generalized Capacitated Fixed-Charge Network Design Problems
David Franz Koza, Erik Orm Hellsten, David Pisinger
Available at SSRN 3704539
Publication date 2020/10/4

Abstract
Capacitated fixed-charge network design problems and generalizations, such as service network design problems, have a wide range of applications but are known to be very difficult to solve. Many exact and heuristic algorithms to solve these problems rely on column-and-row generation (CRG), which frequently suffer from primal degeneracy. We present a set of dual inequalities, equivalent to a simple primal relaxation, that speed up CRG algorithms for generalized capacitated fixed charge network design problems. We investigate the impact of the dual inequalities theoretically as well as experimentally. For practical applications, the presented technique is simple to implement, has no additional computational cost and can accelerate CRG by orders of magnitude, depending on the problem size and structure.