Final *Recommendation*

Title of thesis	**Routing and Scheduling in Feeder Line Operations**
PhD student	***David Sacramento Lechado***
Date of birth	***11-11-1993***
Department	***Department of Technology, Management and Economics***
Supervisor(s)	***Professor David Pisinger, PhD Charlotte Vilhelmsen***
Date of defence	***5-11-2020***

Examiners' assessment

Please write the assessment below – if the assessment is written in a separate document, the document must be signed by all members of the assessment committee

Please address the following topics in relation to the thesis: a) Coherence and scope of research b) Major novel research results obtained c) Significant advancement made to the technical field d) Impact of the research within the research area e) Innovation f) Clarity of the thesis

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The Ph.D. thesis by David Sacramento Lechado is written as a monograph based on 5 journal papers, 2 book chapters and several conference presentations. The thesis is well written with a clear structure and illustrative explanations of the most complex parts of the work.

The thesis has three very clear research questions: How should feeder networks be designed such that they optimise the total network profit with a trade-off between competitive delivery times and operational costs? How should feeder line operators schedule their fleet to improve the operational planning of container vessels in hub ports? What are the overall benefits on the operational planning when increasing the flexibility of operations at container terminals and considering collaborative planning of sea and land transportation? The thesis provides valuable insights to all of the above questions.

The thesis presents several important contributions. Feeder network design is presented as a novel problem and mixed-integer programming and Adaptive Large Neighbourhood Search (ALNS) approaches are devised to solve the problem. The feeder vessel scheduling problem is presented as a collaborative problem in maritime logistics. A mathematical description of the problem is provided which incurs a deeper understanding of the problem with several realistic extensions. Of particular interest are the Constraint Programming (CP) formulations and the hybridized (mixing ALNS and CP) solution methods applied to practically solve the problem.

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The research community will benefit from the classification of liner shipping network design algorithms and the publication of new benchmark instances. The use of hybridized methods where CP or MIP are combined into a heuristic approach is in line with recent developments, and thus will help the research community reach further advances. The successful use of CP within the solution methods is of particular interest as this technique is often overseen.

The candidate's in-depth knowledge about the studied problems and the level of industrial details included in the models have high innovative potential. The results will increase the awareness of the industry on the opportunities raising from the use of optimization methods, and the potential of collaborative planning.

Chapter 1 introduces the context of the thesis giving a clear description of the key concepts in maritime transport and in particular of the containerized industry. The research questions and the structure and contributions of the thesis are furthermore well presented.

Chapter 2 is a very comprehensive introduction to liner shipping network design with a review of important literature within the field. It starts with a comparison between different modes of transportation, mainly with respect to environmental considerations and then introduces the containerized liner shipping network design problem in great detail. This is then contrasted with roro shipping, even though this is not focused on in the chapter. The introduction ends with a discussion of how to calculate emissions and an overview of the LINER-LIB instances.

One of the key contributions of the chapter is the structured classification of algorithms for the liner shipping network design problem. The algorithms are divided into four groups; MIP-based algorithms, two-stage algorithms, subset of routes and backbone flow. All groups are well described and there is a logic to the proposed classification. Still, there are some elements lacking. The distinction between exact methods and heuristics could be clearer, the motivation for the given classification could be more elaborated and alternative classifications should be discussed.

The subsection about mixed integer programming models thoroughly presents a selection of different models. The candidate is able to clearly show the diversity in modelling approaches and the inherent complexity of the problem. The models are in general well described, but the link back to the classification could be stronger. The elements discussed in the classification are not always well highlighted.

The following three subsections discuss the three last groups of algorithms and present the algorithms from the literature in detail. Most of the algorithms are easy to follow and the candidate is once more able to show the diversity of algorithms in the literature.

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The subsection on speed optimization presents the different approaches that have been used, but there is unfortunately not very much discussed about the different options (full service vs. individual legs) or other factors that can affect the relation between speed and fuel consumption such as load on board, hull shape and weather.

The next subsection summarizes the results in the literature on the LINER-LIB instances before the section ends with concluding remarks and future challenges. Here, the candidate shows knowledge and understanding of the business as well as the research and discusses interesting practical challenges and research opportunities.

On the positive side, the candidate has done an impressing job with collecting, reading, understanding and extracting the main elements from the research literature. The candidate shows that he has a thorough understanding of the business as well as the main models and solution methods used.

On the negative side, the structure of the presentation is not always convincing. It is incredibly difficult to write a good review and it must often be restructured a couple of times before everything is in its right place. This section is somewhat fuzzy and the difference between discussing models and methods is not always clear. The section is very descriptive, but occasionally lacks reflections and connections between the material.

Chapter 3 presents an iterative two-phase heuristic for the feeder network design problem (FNDP). The FNDP is defined over a set of ports, where one of the ports is the hub and the other feeder ports. All demands have either their origin or destination in the hub. The fleet is divided into vessel classes, with a given number of vessels of each class. The speed of a service is variable, but the same on all legs of the service. Not all demand must be served, but each demand can be split and served by different services. The objective is to maximize the difference between the revenue from transported demand and the operational costs and penalty for rejecting demand.

The two-stage algorithm follows a common decomposition idea from the literature. The first stage creates a service network and the second stage flows the demand through the network. The first stage starts by creating a set of services by combining simple cycles into more complex services. How the simple cycles are created is not obvious. After the creation of the services, the heuristic adapts the speed of each service.

The second stage of the heuristic is to flow the demand through the network. Since transhipments are rare in a feeder network and the speed of each service is set in the first stage, the flow problem is formulated as a linear program over the simple cycles.

The two-stage algorithm is inserted in an iterative heuristic framework. The heuristic adds a port to a simple cycle in the best possible way, and then runs the two-stage algorithm to

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create a service network and flow the demand. The ports are either greedily or randomly chosen based on the current potential revenue. This is then repeated until n solutions have been created, and the best of these is sent to a local search.

The local search iterates through all simple cycles, remove the simple cycle and insert the removed port visits into other simple cycles in a greedy fashion. After this, the solution is perturbed by removing port-visits and greedily reinserting them in the solution.

The heuristic is tested on three sets of instances; two feeder instances from LINER-LIB, a constructed set of instances based on modified version of LINER-LIB instances and the feeder instances from Ameln et al. (2019). The results are convincing.

On the positive side, the candidate shows a deep understanding of the structure of the problem and creativity in the design of the algorithm. The algorithm combines elements from mathematical programming and metaheuristics in a fascinating way. The computational study shows good results and there are nice discussions about them.

On the negative side, the presentation and structure of the section have room for improvement. The overall structure of the algorithm should preferably be presented before the details so that the reader is familiar with the method before trying to understand the details. The two-stage/two-phase description is confusing. Too little reflection on the design choices made is provided.

Chapter 4 provides an introduction to a feeder routing a scheduling problem for multi-terminal ports and refers to it as the Post Scheduling Problem (PSP). The section starts by generally describing the liner shipping industry and giving a general description of the PSP, motivating its importance. The descriptions and motivation of the work are very clear and well structured. The main contributions are the definition of this novel scheduling problem, the implementation of an Adaptive Large Neighbourhood Search (ALNS) heuristic, and the publication of a new set of benchmark instances.

A thorough literature review identifies the PSP as a new scheduling problem and classifies it as a generalization of the General Shop Problem. The review could have though benefitted from the inclusion of the work of Venturini et al. (2017) where multi-port berth allocation is studied, and where the effects of speed optimization are reported.

The section continues with a well described and novel mixed-integer programming model that formalizes the problem. The cost structure is particularly well described. Following the mathematical model, the ALNS is described. The heuristic is based on a graph representation of the problem, which cleverly uses a transitive reduced ordered disjunctive graph as a way to model and search for solutions within the heuristic framework. The ALNS uses several repair and destroy operators inspired by the vehicle routing litterateur and which have

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been adapted to the PSP and the disjunctive graph representation. The ALNS is further enriched with diversification and intensification techniques such as backtracking, constraint propagation and searches within the i feasible region. The candidate shows mastery over the scheduling theory and a deep understanding of the ALNS framework.

The ALNS is tested on a new set of benchmark instances which are well described and motivated. An extensive set of experiments compares the performance of the ALNS against that of the mathematical model. The tuning of the ALNS parameters and the sensitivity analysis over the parameters of the problem show the candidate scientific maturity. It should also be noticed that, even though the section is motivated by a reduction on sailing speed, this is not quantified or discussed.

Chapter 5 deals with the problem of routing and scheduling feeder vessels in multi-terminal ports. The main contribution of this section is a combination of an Adaptive Large Neighborhood Search (ALNS) heuristic with an exact CP approach. The section provides a very good introduction to the general domain of the liner shipping industry, defining the vocabulary and the different types of problems occurring in this field. It then focuses on an informal description of the studied problem that arises in the context of large multi-terminal hub ports where feeder vessels transport the containers between the hubs and the feeder ports. The description of this important problem and of the context of the study (literature review, existing test instances) is very clear and complete.

A Constraint Programming (CP) formulation of the problem is provided using the modelling concepts of CP Optimizer (CPO). The formulation elegantly leverages these concepts and the resulting model is very simple and compact (7 lines).

Some very convincing experiments are performed with this CP formulation on the existing benchmarks showing that it is in average more efficient than existing MIP models.

Next, the section presents an ALNS meta-heuristic to solve the problem, the approach is based on deciding on the sequencing of the operations, both from the vessels and from the terminals point of view. While the ALNS itself does not outperform the CP formulation, the rest of the section proposes a way to integrate both approaches and exploit their complementarity. In the integrated ALNS-CP math-heuristic, solutions are shared and exchanged between the two components that can improve them. A very detailed experimental study shows that the resulting approach clearly outperforms each of the individual components.

Overall, this section is an important contribution to the understanding and resolution of the problem of routing and scheduling feeder vessels in multi-terminal ports. The candidate proposes using and adapting different existing frameworks (ALNS, CP) and combining them into a very efficient approach for solving the problem.

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Chapter 6 studies an extension of the problem described in section 5. More precisely two extensions are proposed to make the problem more realistic. These extensions are clearly justified from an applicative point of view:
- the possibility to use several berths at the same time at a given terminal, allowing to process multiple operations in parallel (multiple berths), and
- the possibility to exploit multi-mode transportation (by sea or land) so that the operations can be performed at a different terminal than the one initially planned (collaborative planning).

The CP formulation presented in section 5 is extended, using cumul functions for multiple berths and alternative constraints for collaborative planning. Just like in section 5, these formulations smartly exploit the modelling concepts of CPO for scheduling problems. Some extensive experiments are performed with this formulation to draw interesting conclusions on the trade-off between the different degrees of freedom brought by these two extensions.

Appendix A presents additional work to the core topics of the thesis. Specifically, it presents a novel routing problem, the Vehicle Routing Problem with Drones (VRP-D). Aside from studying a new and relevant routing problem, the main contributions of this section are a novel mathematical formulation, an ALNS algorithm to solve the problem and an extensive set of computational experiments.

The section starts by using commercial test of drone distributions as a way to motivate the importance of the problem and continues with a thorough literature study. The candidate identifies the most relevant research and clearly states the differences and contributions to the state-of-the-art. A possible improvement could a be a brief discussion on the privacy issues in relation to drone deliveries and its actual feasibility in urban areas.

A mathematical model is presented for the VRP-D as an extension of the state-of-the-art model for a single truck version of the problem. The model is well described, particularly the constraints related to the synchronization between the drones and the trucks.

An ALNS algorithm is devised to solve the problem which first uses heuristic procedures to identify the routing of the trucks and then employs insertion heuristics to add drone deliveries to the solution. On the positive side, several repair operators have been studied to better integrate drone deliveries into the ALNS framework, while the destroy operators seem to not have received as much attention. The cluster destroy method is designed to improve drone deliveries, while truck routing improvement are left to a simple random removal. Nevertheless, the ALNS performs well on the benchmark set.

An extensive set of computational results shows once again the candidate research maturity and interest in finding in-depths insights on the algorithms performance. The results are based on a new set of benchmark instances. The development of a new set of in-

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stances is motivated by the lack of publicly available real-life case data. The set of instances is well described, and it is clear that lots of attention has been paid to make the benchmark as realistic as possible.

References:

Marie Ameln, Julie Sand Fuglum, Kristian Thun, Henrik Andersson, Magnus Stålhane, A new formulation for the liner shipping network design problem. International Transactions in Operational Research. (2019), https://doi:10.1111/itor.12659

Giada Venturini, Çağatay Iris, Christos A. Kontovas, Allan Larsen, The multi-port berth allocation problem with speed optimization and emission considerations, Transportation Research Part D: Transport and Environment, 54, 142-159, (2017), https://doi.org/10.1016/j.trd.2017.05.002.

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Please address the following topics in relation to the defence: a) Selection of topics from the Thesis b) Overview demonstrated c) Lecturing ability of the candidate d) Ability to answer questions at the defence

During the defence, the candidate gave a very good presentation of the topics covered by the thesis. Through a wise use of illustrations and examples, the main contributions of the thesis were highlighted. The candidate demonstrated scientific maturity and answered all the questions from the committee to full satisfaction. The committee also finds that the candidate has clearly proved to be able to enter into in-depth discussions reflecting on the advantages and shortcomings of his findings.

In conclusion, the assessment committee finds that the thesis and the defence more than meet the requirements and we recommend that **the candidate be awarded the PhD degree**.

The examiners of the thesis hereby submit the following recommendation:

[X] The PhD degree should be conferred with reference to the above/enclosed assessment

[ ] The PhD degree should *not* be conferred with reference to the above/enclosed assessment

The recommendation is

[X] Unanimous

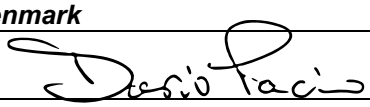
[ ] Divided

In the event of disagreement, the majority will decide.

Thesis examiners:

Chairman

Title, name, affiliation ***Assoc. Professor Dario Pacino - Technical University of Denmark, Kgs. Lyngby, Denmark***

Date 5/11/2020 Signature 

Title, name, affiliation ***Professor Henrik Andersson - Norwegian University of Science and Technology, Trondheim, Norway***

Date 5/11/2020 Signature 

Title, name, affiliation ***Principal Scientist Philippe Laborie - IBM, Data and AI, Saclay, France***

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