Design and Operation of Low/Zero Emission Vessels

State-of-the-art and potential developments

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MIIP no. 012

December 2020

Summary

Expanding on the previous report,which focused on the design and operation of on-board power systems and identified possible research directions, this report will explore areas related to the interactions between vessels and infrastructures. Additionally, two of the research ideas proposed in the first part of the project is expanded and structured in preparation for a grant proposal. More information on the project and it's approach is given in Section 1

Innovation in on-board power systems can come either in the form of electrification or via the use of alternative power sources. The latter can mean either internal combustion engines using non-diesel fuels, batteries or fuel cells. Regardless of which of these options is used, the effectiveness and autonomy of the ships will be highly dependent on the availability of the necessary infrastructure. The development of the supporting infrastructure has been analysed independently from ship design in the past. Section 2 provides an overview of how simultaneous analysis and development in these two areas can be beneficial and proposes a framework which would enable this approach. Joint research projects are scarce, but a list of on-going projects in the area of infrastructure is provided.

The following two sections will each explore on one of the three research directions identified in the previous report. One of the ideas (Scalability of various energy systems) was abandoned due to lack of interest. The remaining two ideas been expanded and adapted to include the feedback received from our industry partners. Additionally, for each of the two ideas we propose a way to account for the interdependency between ship and infrastructure development.

- *Integration of RAMS concerns in system design and operation:*
  This idea has been split into two distinct (but related) areas of research: integrating reliability into existing algorithms for sizing and EMS and fault detection and isolation.

- *Streamlined electrification:*
  Starting from the original proposal of focusing on retrofitting to account for the long service life typical of the maritime sector, the scope has been restricted to electrification. We propose that existing research into the logistics of maintenance and retrofitting, combined with the relatively low variability in inland vessels can be used to determine a parametrized optimization algorithm for the design and/or planning of the electrification process.

?? concludes the report by outlining the work done within the NoMES project and the potential identified for future research. A focus is placed on versatility and how the presented information and research directions can be integrated into wider scoped projects and grant proposals.

Contents

1 Project Introduction

NoMES is a project funded by NML which aims to study the state-of-the-art research landscape regarding the design and operation of Low/Zero Emission Vessels. This report covers the second part of the project, focusing on ship-infrastructure interactions but also expands on the ideas explored in the preceding report. For the sake of clarity,the stated NoMES objectives will be reproduced here.

1. *Power and Propulsion:* Design of the power and propulsion system and the selection of its components (battery, fuel cell, diesel-generators, electric motors, and power electronics) with regard to the ship type and its operating profile in order to increase reliability and lifetime of the components and to decrease fuel consumption and environmental footprints.
2. *Energy Management:* Study of energy management, power availability, and power system stability in the presence of new energy sources onboard. Designing novel approaches and algorithms for energy management and power generation control, taking into account component lifetime and class regulations to maximize fuel efficiency, minimize emissions, improve system robustness and stability.
3. *Ship-Infrastructure Interactions:* Study of the interaction of the vessels with the shore side infrastructure, such as renewable energy sources, battery chargers, the electricity grid, and bunkers of new fuel types, in urban and port areas and the study of logistics around this interaction.

The second stage of the project began with a workshop in which the results of the research done in the areas of Power and Propulsion and Energy Management were presented and discussed. The goals pursued through this workshop have been achieved:

- Transfer of knowledge of the most relevant information resulting from the review of academic literature;
- Presenting potential research directions to our industry partners;
- Gathering feedback and reshaping the proposed ideas as necessary.

Following the workshop, we decided two abandon one of the three ideas and better define the scope and objectives of the remaining two. Additionally, a literature search was performed for the last of the NoMES key challenges: Ship-Infrastructure Interactions. Due to the scarcity of research investigating explicitly the interdependency between the two areas, the literature research ended up revealing more research exclusively on infrastructure and logistics. To that effect, the focus was adjusted to identifying the key challenges of tackling the two research fields in a holistic way. A case is made for the necessity of accounting for uncertainty and Decision Based Design is presented as a potential solution.

The core information reported on in the current document has already been presented to our industry partners during a second workshop and received feedback has been integrated.

2 Ship-Infrastructure Interactions

As the subject covered in this section is rather elusive and unexplored, clarity is particularly important. To that effect, merely defining the scope of the present investigation is insufficient and the first part of this section will also provide a more extensive overview of the subject and the key challenges expected. Afterwards, a framework is proposed that would be able to account for these challenges and allow for the development of joint optimization ans analysis tools. A non-exhaustive list of relevant Dutch and European maritime infrastructure related projects is provided.

2.1 Key challenges in ship-infrastructure interactions

The economic aspects of the interactions between ship and infrastructure are getting increasingly harder to separate from technical aspects and crucial design decisions. Logistics, economic analysis and policy development all play a roll in the development of both ships and their supporting infrastructure. Each of these areas corresponds to an entire field of research, for the purpose of this project, we want to explore the potential and challenges of analysing/optimizing/developing ships and infrastructure simultaneously.

Historically, it makes sense that the two research fields would develop more-or-less independently and the inter-dependency of the industries would be governed by market forces. However, there are at least two recent developments that support the benefits of a joint approach:

1. *Relevance of a ship's detailed operational profile on design:* While some information on the future operations of the ship was obviously always part of the design process, the following three considerations are specific to the modern landscape.
    - The relative efficient of adopting electric propulsion over mechanical propulsion is dependent on the operational profile [Georgescu et al., 2017], the same hold true for adding on-board energy storage [Georgescu et al., 2018].
    - Operational measures have been shown to be one of the most effective way of reducing CO_2 emissions [Yuan and Ng, 2017].
    - Adoption of energy storage means that defining the operational profile simply as a distribution capturing the relative frequency of various loading points is no longer sufficient. Information on the loading profile over time is necessary in order to size the battery and develop effective energy management and control strategies.
2. *Environmental Concerns:* Various policy measures have been implemented in order to internalize costs related to pollution [Vierth and Merkel, 2020], however this hasn't been shown to be sufficiently effective (when combined with market forces) in order to assure cooperation [Jazairy, 2020]. Following an analysis of the current state of Greenshipping in various countries Lee and Nam [2017] showed the potential of increased information sharing and joint cost reductions.

Despite these developments, research focusing specifically on the interactions and interdependencies between ship and infrastructure has been scarce. Existing studies tend to be focused on costs and are unidirectional. Due to the complexity of the issue, such restrictions are not surprising. Some of the key challenges are listed bellow:

- *Uncertainty:* Engineering design often comprises of complex trade-offs, but any uncertainty can usually be accounted for by safety factors. As the environment is an increasing relevant criteria, design decisions become more and more reliant on outside factors which are governed by uncertainty:
  - **Policy** has an increasing impact on any cost analysis and life-cycle assessments due to subsidies and taxes aimed at internalizing costs [Lee and Nam, 2017] [Perčić et al., 2020]. For example, Keller et al. [2019] shows that without policy interventions, implementation of alternative fuels can result to a maximum of 3% emission reductions.
  - Another source of uncertainty comes from the **market** and is best reflected by uncertainty in fuel prices.
  - Lastly, uncertainty also results from the inaccuracy of modelling tools, estimations and assumptions used in **technical design**.
- *Feedback loops:* The most noticeable example is how the feasibility of ships powered by alternative fuels and charging stations are primarily dependent on the current and projected adoption levels of a particular fuel by the other. Other bi-directional relations are more subtle. For example, in investigating the emergence of hydrogen as fuel, de Graaf et al. [2020] lays out significant geopolitical consequences to a potential switch from oil.
- *Information format and transfer:* Information is usually condensed into concepts and parameters which are considered relevant for a given field. Additionally, stochastic processes and economic analysis also use a different mathematical framework than technical design. This makes integrating information from across all relevant fields particularly challenging.
- *Competing interests:* While it can be reasonably assumed that the interests of shipyards, ship operators and port administrators are aligning when it comes to protecting the environment, the same obviously doesn't hold true when it comes to economic considerations.

2.2 Uncertainty, probabilistic framework and decision based design

As opposed to risk analysis, accounting for uncertainty deals with a much larger variety of probabilities and generally requires a more holistic approach. In design, uncertainty analysis is usually focused on quantifying uncertainty and tracking down it's sources [Vrijdag, 2014] [Vrijdag, 2014]. The most popular approach is to distil the uncertainty of market and policy evolutions into distinct scenarios. However, this method is not suitable for increased degrees of complexity. A simplified situation is shown below.

The example chosen looks at the potential benefits in fuel price that can result from a switch from one diesel to multiple diesel or dual-fuel engines. While the trade-offs of choosing an alternative fuel are significantly more complex [Deniz and Zincir, 2016], we will use a simplified version in order to show how uncertainty is challenging to account for even in such a simplified case. The decision variables are the number of engines and the choice between one of the two engine types. The uncertain factors taken into account are the operational profile, market fuel prices and the evolution of environmentally protected areas (Figure 1)

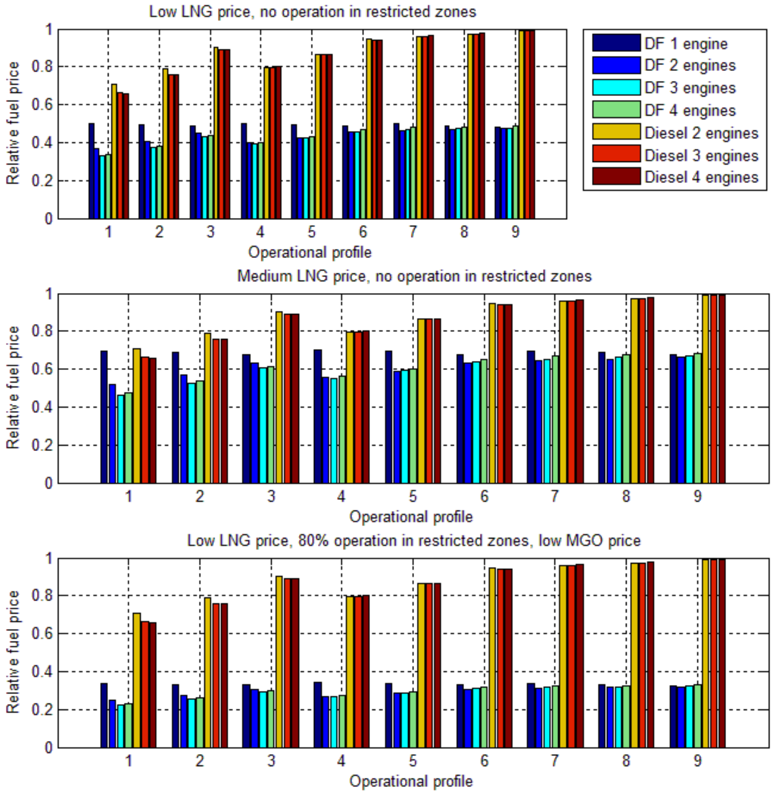

Figure 1: Relative fuel costs resulting from installing a dual-fuel engine relative to a conventional diesel engine for nine different operational profile

It can be seen that while the number of engines has a relatively small impact, the other uncertain factors interact with others in non-obvious ways. The figures above are only a small selection of the total number of scenarios possible from the chosen variables and already, arguably, provide too much complexity to be effective as decision support.

In order to provide a manageable framework for processing such information, Hazelrigg [1998] proposed adapting concepts from the area of decision theory (typically used in economical and policy analysis) to engineering design.

As opposed to typical engineering design tools, this one introduces normative elements, while maintaining the expected mathematical rigour. It can therefore provide assistance not only in handling uncertainties, put also in guiding complex trade-offs between multiple evaluation criteria.

At the core of the framework is the concept of utility [Thurston et al., 1994]. Utility integrates information from multiple criteria (usually, but not necessarily via weight factors) and multiple scenarios into one number. In our example, a single evaluation criteria is used (fuel costs), but three different price points are considered for each fuel and three different policy scenarios which would result in different fuel requirements. Just these factors would require 81 separate figures in order to show the whole picture. By calculating the utility factor (which in this case is as simple as multiplying the likelihood of a scenario with it's associated fuel price), we can condense this information in **??**

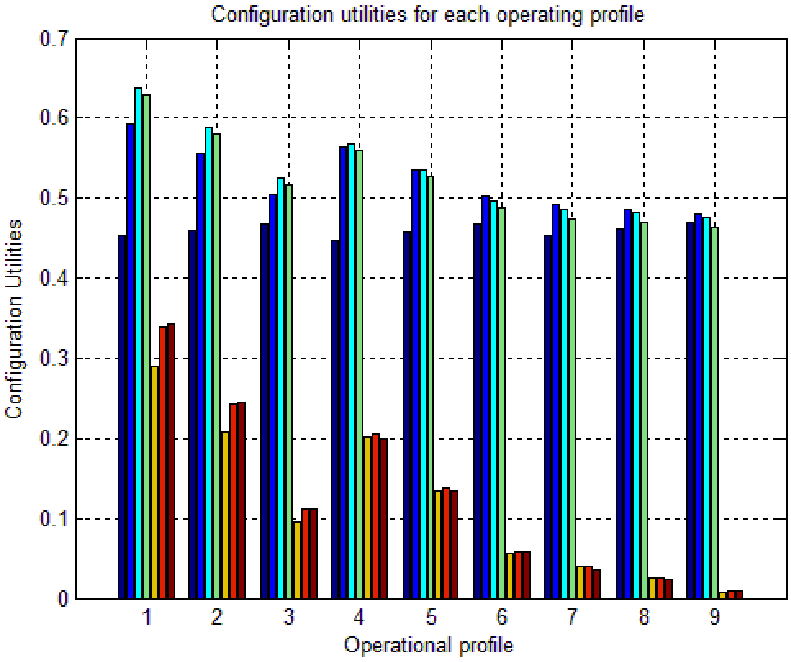

Figure 2: Expected relative utility for different configurations and different operational profiles compared to a benchmark configuration consisting of one diesel engine

Being a fundamentally normative tool, it has significant limitations which need to be taken into account [Thurston, 1999]. We don't recommend it for detailed design, but propose that it is well suited and arguably even necessary in order to simultaneously account for the perspectives of both ships and infrastructure when, for example, evaluating alternative fuels.

2.3 Recent and On-going research projects

This section comprises of a list of recent and on-going research projects that were considered relevant to the scope of this report: alternative fuels and the development of infrastructure. We mention again that the list is not exhaustive and additions are welcomed. The projects are listed in no particular order and the description provided is copied/paraphrased from the included links.

FASTWATER (FAST Track to Clean and Carbon-Neutral WATERborne Transport through Gradual Introduction of Methanol Fuel: Developing and Demonstrating an Evolutionary Pathway for Methanol Technology and Take-up.) he EU-funded FASTWATER project aims to reduce its greenhouse and pollutant emissions by using methanol fuel. FASTWATER elaborates an evolutionary pathway for methanol, including retrofit solutions. The project will develop retrofit kits and methanol engines and demonstrate these in a harbour tugboat, a pilot boat and a coast guard vessel. A methanol powered river cruise vessel design is also included, as well as logistics and bunkering, revision of rules and regulations, and crew training. Eventually, FASTWATER will implement business plans including the life cycle performance analysis of costs, CO2 and pollutant reductions, to commercialise the developed solutions.

sEEnergies(A holistic approach to the energy efficiency potential in Europe) The Energy Efficiency First principle policies impact can mitigate the energy-related carbon dioxide emissions and help achieve net zero emissions in the EU by 2050. Achieving this requires a greater understanding of the energy efficiency potential at a sectorial level and in each country. It also needs an energy system perspective that looks at the interlinkages between the different sectors. The EU-funded sEEnergies project aims to conduct a comprehensive assessment and quantification of the Energy Efficiency First principle policies impact and will develop a holistic framework that takes into account the synergies between different sectors to maximise energy savings. A large part of work will revolve around temporal and spatial models, as well as geographical information systems so that the energy efficiency potential can be quantifiable and visible in each country.

ZEFER(Zero Emission Fleet vehicles For European Roll-out) The project will deploy 180 FCEVs (Fuel Cell Electric Vehicles) in Paris, London and Brussels. It will demonstrate the viable business cases for captive fleets of FCEVs in operations which can realise value from hydrogen vehicles.

NEPTUNE(New Cross Sectoral Value Chains Creation across Europe Facilitated By Clusters for SMEs' Innovation in Blue Growth)NEPTUNE aims at developing new cross-sectoral and cross-border industrial value-chains, including notably SMEs, to foster the development of Blue Growth industries in Europe and beyond. This will be based on the construction or reconfiguration of value chains driven by the integration of new technologies and know-how between Water, Aerospace, ICT and Agriculture industries. NETPUNE addresses in particular three key aspects of Blue Growth that have a great potential to benefit from such collaboration and SME innovation support: (i) Water management in urban and rural environments; (ii) Fluvial and maritime transport and port logisitics; (iii) Environment and renewable marine energy.

From a methodological perspective, NEPTUNE focuses on two main concepts: the innovative Open Space Platform that refers to the collaborative space and innovation animation techniques via a project emergence methodology that helps SMEs and other stakeholders to identify market trends and opportunities and support the incubation of Blue Growth projects and innovation ideas. NEPTUNE expects to support at least 100 SMEs for the development of 40 new innovative solutions. NEPTUNE brings together 10 of Europe's leading clusters from 7 countries and 2 additional innovation, creativity and inter-cluster expert organisations to implement this ambitious project.

SeaTech(Next generation short-sea ship dual-fuel engine and propulsion retrofit technologies)A consortium of eight industry and academic partners is conducting a 3-year research project to develop two symbiotic ship engine and propulsion innovations. The EU-funded SeaTech project will develop an operational version of an oscillating flapping-wing propulsion device and test the energy saving device aboard short-sea vessels. The innovation will be characterised by high retrofitability and maintainability. It will also offer shipowners a return-on-investment of 400 % due to fuel and operational cost savings. The project estimates CO2 savings of 32.5 million tonnes annually if just 10 % all EU short-sea vessels are retrofitted with SeaTech.

MOMENTUM(Modelling Emerging Transport Solutions for Urban Mobility) The goal of MOMENTUM is to develop a set of new data analysis methods, transport models and planning support tools able to capture the impact of new transport options on urban mobility, in order to support cities in the task of designing the right policy mix to exploit the full potential of emerging mobility solutions. The specific objectives of the project are:

1. Identify a set of plausible future scenarios for the next decade to be taken into account for mobility planning in European cities, considering the introduction of disruptive technologies such as CAVs.
2. Characterise emerging activity-travel patterns, by profiting from the increasing availability of high-resolution spatio-temporal data collected from personal mobile devices and digital sensors.
3. Develop data-driven predictive models of the adoption and use of new mobility concepts and transport solutions, in particular MaaS and shared mobility, and their interaction with public transport.
4. Provide transport simulation and planning support tools able to cope with the new challenges faced by transport planning, by enhancing existing state-of-the-art tools with the new data analysis methods and travel demand models developed by the project.
5. Demonstrate the potential of the newly developed methods and tools by testing the impact of a variety of policies and innovative transport services in different European cities with heterogeneous sizes and characteristics, namely Madrid, Thessaloniki, Leuven, and Regensburg, and evaluating the contribution of the proposed measures to the strategic policy goals of each city.
6. Provide guidelines for the practical use of the methods, tools and lessons learnt delivered by the project in the elaboration and implementation of SUMPs and other planning instruments.

HyLIFT The aim of HyLIFT-EUROPE is to demonstrate more than 200 fuel cell materials handling vehicles and associated refuelling infrastructure at

2 sites in Europe, making it the largest European trial of hydrogen fuel cell materials handling vehicles so far. The project efforts are in continuation of the previous FCH JU supported HyLIFT-DEMO project. In the HyLIFT-EUROPE project the partners demonstrate fuel cell systems in materials handling vehicles from the partner STILL and other non-participating OEMs.

Eco Edge Prime Power This project aims to create a proof of concept (POC) alternative prime power source that employs fuel cell technologies for on-site power generation, which are efficient, quiet, showing reduced environmental impact and negligible demand on the electrical grid. Fuel cells have been around since the Apollo space program and can operate on different fuels like natural gas, hydrogen and propane (LPG). Fuel cells are electrochemical energy converters with efficiencies that exceed conventional power plants, already at small scale. The concept of connecting fuel cells to gas networks to power resilient urban and edge data centres overcomes the need to have backup generation in such areas, thus reducing the emissions and noise impact.

REVIVE(Refuse Vehicle Innovation and Validation in Europe) REVIVE will significantly advance the state of development of fuel cell refuse trucks, by integrating fuel cell powertrains into 15 vehicles and deploying them in 8 sites across Europe. The project will deliver substantial technical progress by integrating fuel cell systems from three major suppliers and developing effective hardware and control strategies to meet highly demanding refuse truck duty cycles. Specific work on standardisation will ensure that the lessons learned are applicable to the full range of OEMs supplying vehicles into the European market, helping to accelerate the introduction of next generation products. In parallel, the demonstration activities will greatly raise awareness of the viability of fuel cells as a solution to demanding heavy duty vehicle uses (and raise public awareness of hydrogen mobility more generally due to the visibility of the trucks).

ELECTROU will install the first MW fuel cell in Europe fully integrated into a building at the high profile redevelopment at Kings Cross, London. This includes the full use of power & heat generated by the fuel cell within the local building, the site wide heat, power and cooling networks, and extends to water re-use and support of the micro grid.

GASVESSEL aims to prove the techno-economic feasibility of a new CNG transport concept enabled by a novel patented Pressure Vessel manufacturing technology and a new conceptual ship design including safe on- and offloading solution. It carries out research and innovates different steps in the value chain from a decision support model to simulate and benchmark scenarios until the process of ship design, new Pressure Vessel designs and manufacturing as well as novel high pressure on- and offloading.

The validation and proof of concept of the GASVESSEL project is performed by a cost-benefit analyses (financial viability), safety assessment, environmental impact analyses and value chain business cases development in relation to real-life geo-logistic scenarios.

3 Streamlined electrification

3.1 Overview and potential

The general benefits of retrofitting and it's particular appeal to the maritime industry have been investigated and presented in the first stage of the project. We were initially interested in the idea of breaking down the retrofitting process into distinct modules which would allow for an incremental implementation. This path turned out to be infeasible and, following an informative discussion during the first NoMES workshop, it became apparent that modularity can better be used in order to streamline the process.

Additionally, the scope was reduced to the retrofitting of inland vessels. The proposed approach is particularly suited for this sector as it is characterized by having multiple small operators (which can significantly benefit from sharing design costs) and more-or-less standardized ship types. From the multiple avenues possible for the retrofitting of in-land vessels we decided to focus on electrification as it is provides the most versatility and is the less reliant on the development of infrastructure. However, a similar approach can be used for the implementation of alternative fuels if the approach proposed in Section 2 is used.

Streamlining electrification can occur in both design and implementation. As the latter would fall under the umbrella of Operations Research, we wish to focus on design. To that effect, the aim is to achieve a parametrized optimization algorithm for the new on-board power system. This can be achieved by first identifying similarities and patterns in the electrification process of different vessels and using these results to modularize the design.

3.2 Proposed research approach

In order to achieve the stated goal we propose the following breakdown of research objectives:

1. Parametrization of major design inputs
    - Operational profile
    - Infrastructure constraints
    - Schedule constraints
    - Existing system
2. Investigate the applicability of operation research on data and design
3. Investigate the potential for modularization of the electrification process
4. Quantify the costs incurred by lack of availability
5. Develop a method for quantifying versatility
6. **Parametrized optimization of a complete retrofitted solution**

4 Reliability Availability Maintenance Safety (RAMS) of modern energy systems

4.1 Overview and potential

The first report gave an overview of the common approaches used in RAMS study and the major areas of research. One of the most interesting and active areas in in the integration of RAMS concerns (particularly longevity) into energy management strategies. Extending the scope to autonomous shipping points out another interesting and increasingly relevant area of research: fault detection ans isolation. Lastly, the considerations above (and many others!) indicate significant changes in this field in the coming years which is likely to have unknown consequences and place increased demands on infrastructure.

4.1.1 RAMS as part of EMS

The longevity of batteries [Hu et al., 2015] and fuel cells [Kandidayeni et al., 2020] can be extended by improved management of dynamic loading and temperature. Moreover, as shown by Kandidayeni et al. [2020], the state of health of fuel cells is not only an optimization goal, but also an important parameter when optimizing for energy efficiency. The impact of ageing was shown by using fuel cells at two different states of degradations, it can be reasonably expected that the benefits would be increased if a continuous approach to degradation is considered.

Of note, is also the fact that any progress in this area can be developed on top of already existing EMS strategies, thus unlocking the advantages of using a holistic approach.

4.1.2 RAMS in the context of autonomous shipping: Fault Detection and Isolation

In control and systems, Fault Detection and Isolation (FDI) is referred to a field of research in which the aim is to supervise a system performance, detecting occurrence of a fault, pinpointing its location and then, applying a set of strategies to compensate its effects [Hwang et al., 2010]. In a hybrid ship with an advanced power and propulsion system, which is classified as a complex system, the occurrence of fault is quite probable. It is quite critical that a set of FDI algorithms are applied to increase the system robustness and resistance to fault. With the integration of novel energy sources into the advanced power and propulsion systems, several failure scenarios should be considered (e.g., failure of electrical sensors or primary and secondary power sources) and proper protocols to detect and isolate them should be developed.

The classical limit-value-based supervision methods are simple and reliable, but they are only able to react after a relatively large change of a feature, i.e. after a large sudden fault or a long-lasting gradually increasing fault. Therefore a method is needed, which satisfies the following requirements:

- Early detection of small faults with abrupt or incipient time behaviour;
- Diagnosis of faults in the actuator, process components or sensors;

- Detection of faults in closed loops;
- Supervision of processes in transient states.

An FDI algorithm/protocol must satisfy all four above mentioned requirements. Three different kinds of fault can occur: abrupt faults, incipient faults and intermittent faults [Isermann, 2017]. Abrupt faults are the most relevant faults in regard to safety issues. Sudden failure can have catastrophic consequences. Incipient faults are more connected to maintenance problems, where early detection of worn equipment is required. These faults are typically small and not so easy to detect [Frank, 1990]. FDI approaches can be classified into different subcategories. The main two categories are model-based and none model-based approaches. In Figure 3, these different approaches are presented [Venkatasubramanian et al., 2003]. For a ship with an advanced PPS, different components and faults might require different FDI schemes. This depends on the nature of the fault, component's model and process, and the control approach and architecture that is supervising the component. Moreover, the effect of integration should be studied on the component level as well as the system level. As a result, it is not unexpected if different FDI approaches are taken on-board for different types of problems.

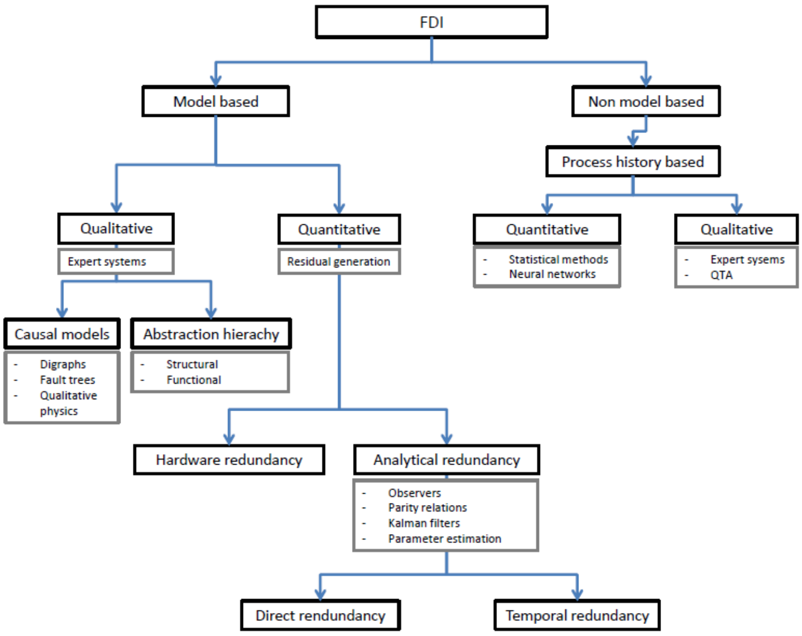

Figure 3: Classification of FDI approaches

4.1.3 Impact of changing RAMS practices on infrastructure

Even if full autonomous shipping is still far away, there has been a consistent trend in recent years of reducing the number of the maintenance crew on board.

To the best of our knowledge, the impact of these emerging trends on infrastructure and the associated opportunities for optimization and automation have not yet been explored. For example, the benefits of CBM are augmented in autonomous shipping and wide implementation can lead to feasible on-demand pre-emptive maintenance in ports.

4.2 Proposed research approach

Future energy systems in combination with PPS require a deeper analysis of the failure mechanisms, ageing and effectiveness of maintenance interventions of batteries and fuel cells. Moreover, advanced reliability optimization mechanisms are necessary in design and during service. These will increase the RAMS of the future vessels by proper interventions in the design stage. However, during operation other strategies and approaches should be picked up to maximize RAMS. The first one is FDI. Complex and advanced PPS of the future require advanced FDI mechanisms to increase autonomy, reliability, and safety during operation. FDI failure proof the overall system in the presence of different types of faults during service. The second type of approaches are embedded in the way that the PPS operates facing different operating profiles and missions. As a result, the energy and power management approaches should be redesigned based on RAMS metrics. The increased autonomy of future vessels in combination with FDI will massively change the way that maintenance is handled. A lot of redundant components will not go on-board in the wake of crew size decrease and increased autonomy. As a result, the infra and logistics around it should be rearranged and prepared based on the real-time data receiving from the vessels.

All these considered, the following research lines are proposed to increase autonomy, survivability, reliability, safety and efficiency:

- RAMS-based analysis and design for future vessels;
- Fault-detection and isolation for advanced PPS;
- RAMS-based energy and power management for various operating conditions;
- Impact of autonomous shipping on logistics and infrastructure of ship maintenance and repair.

5 Conclusions and Recommendations

The NoMES project has started from a very wide scope and necessarily had to cover a lot of material. It thus provided a great opportunity to fully engage with a very existing period for the energy sector as a whole and for the maritime world in particular. The research landscape is very varied, with an undeniable and reassuring focus on the environment.

Within this landscape, there has been a slow but steady move towards holistic optimization methods for design, energy management and control. Several parallel approaches are being developed, but there is a unifying trend in the addition of both options in power sources and evaluation/optimization criteria. It is therefore important that the tools developed and used within our consortium remain competitive. Right now, the way to achieve this is by integrating RAMS concerns into our existing set of algorithms.

On the other hand, retrofitting is a largely unexplored area in academia. So far most projects appear to have been done on a ship by ship basis. A birds eye view of the retrofitting process and streamlining can therefore have significant potential. Any compromises in the optimality of design that can result from a shared retrofitting process is likely to be offset by the reduction in design and implementation costs.

In order to remain pragmatic, we tried to align the second part of the project with upcoming funding potentials. Our initial interest in RAMS has been channelled towards the particularities of autonomous shipping in order to comply with the recent NWO funding opportunity: Maritime hightech: maritime hightech for a secure sea. Bits and pieces of the ideas explored can be repackaged to fit into larger proposals. Similarly, special attention has been placed in the second part of the project on the particularities of the inland shipping sector and how they impact retrofitting in preparation of a separate expected funded opportunity which targets that segment of the maritime industry.

Additionally, complying with original NoMES objectives, we investigated and found ways in which these research topics can be integrated with developments and research in the are of infrastructure. As this report was hopefully able to show, a close cooperation between the two fields is necessary in order to fully achieve the possible environmental benefits provided by emerging technologies. The challenges for such a joint approach are significant, but fit very well within the framework provided by Decision Based Design and could probably benefit by other statistical and mathematical tools.

While writing the two reports, a deliberate effort was made to systematize the information accumulated into a simple and transparent structure. This should allow the integration of parts of the issues presented into many future projects, as the opportunities arise.

References

T. V. de Graaf, I. Overland, D. Scholten, and K. Westphal. The new oil? the geopolitics and international governance of hydrogen. *Energy Research & Social Science*, 70:101667, dec 2020. doi: 10.1016/j.erss.2020.101667.

C. Deniz and B. Zincir. Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production*, 113:438–449, feb 2016. doi: 10.1016/j.jclepro.2015.11.089.

P. M. Frank. Fault diagnosis in dynamic systems using analytical and knowledge-based redundancy: A survey and some new results. *automatica*, 26(3):459–474, 1990.

I. Georgescu, M. Godjevac, and K. Visser. Early efficiency estimation of hybrid and electric propulsion systems on board ships. In *2017 IEEE Vehicle Power and Propulsion Conference (VPPC)*, pages 1–5. IEEE, 2017.

I. Georgescu, M. Godjevac, and K. Visser. Efficiency constraints of energy storage for on-board power systems. *Ocean Engineering*, 162:239–247, 2018.

G. A. Hazelrigg. A framework for decision-based engineering design. 120:653–658, 1998. ISSN 1050-0472. doi: 10.1115/1.2829328.

X. Hu, L. Johannesson, N. Murgovski, and B. Egardt. Longevity-conscious dimensioning and power management of the hybrid energy storage system in a fuel cell hybrid electric bus. *Applied Energy*, 137:913–924, jan 2015. doi: 10.1016/j.apenergy.2014.05.013.

I. Hwang, S. Kim, Y. Kim, and C. E. Seah. A survey of fault detection, isolation, and reconfiguration methods. *IEEE Trans. Control. Syst. Technol.*, 18(3): 636–653, 2010. doi: 10.1109/TCST.2009.2026285.

R. Isermann. Supervision, fault-detection and fault-diagnosis methods – a short introduction, 2017.

A. Jazairy. Aligning the purchase of green logistics practices between shippers and logistics service providers. *Transportation Research Part D: Transport and Environment*, 82:102305, may 2020. doi: 10.1016/j.trd.2020.102305.

M. Kandidayeni, A. Macias, L. Boulon, and S. Kelouwani. Investigating the impact of ageing and thermal management of a fuel cell system on energy management strategies. *Applied Energy*, 274:115293, sep 2020. doi: 10.1016/j.apenergy.2020.115293.

V. Keller, B. Lyseng, C. Wade, S. Scholtysik, M. Fowler, J. Donald, K. Palmer-Wilson, B. Robertson, P. Wild, and A. Rowe. Electricity system and emission impact of direct and indirect electrification of heavy-duty transportation. *Energy*, 172:740–751, apr 2019. doi: 10.1016/j.energy.2019.01.160.

T. Lee and H. Nam. A study on green shipping in major countries: In the view of shipyards, shipping companies, ports, and policies. *The Asian Journal of Shipping and Logistics*, 33(4):253–262, dec 2017. doi: 10.1016/j.ajsl.2017.12.009.

M. Perčić, I. Ančić, and N. Vladimir. Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the croatian short-sea shipping sector. *Renewable and Sustainable Energy Reviews*, 131: 110028, oct 2020. doi: 10.1016/j.rser.2020.110028.

D. L. Thurston. Real and misconceived limitations to decision based design with utility analysis. *Journal of Mechanical Design*, 123(2):176–182, jul 1999. doi: 10.1115/1.1363610.

D. L. Thurston, J. V. Carnahan, and T. Liu. Optimization of design utility. 1994.

V. Venkatasubramanian, R. Rengaswamy, S. N. Kavuri, and K. Yin. A review of process fault detection and diagnosis: Part iii: Process history based methods. *Computers & chemical engineering*, 27(3):327–346, 2003.

I. Vierth and A. Merkel. Internalization of external and infrastructure costs related to maritime transport in sweden. *Research in Transportation Business & Management*, page 100580, oct 2020. doi: 10.1016/j.rtbm.2020.100580.

A. Vrijdag. Estimation of uncertainty in ship performance predictions. *Journal of Marine Engineering & Technology*, 13(3):45–55, dec 2014. doi: 10.1080/20464177.2014.11658121.

J. Yuan and S. H. Ng. Emission reduction measures ranking under uncertainty. *Applied Energy*, 188:270–279, feb 2017. doi: 10.1016/j.apenergy.2016.11.109.