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Visions Far Ahead of Reality

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Abstract

This paper presents a critical review of key IT technologies used in the maritime industries. The techniques are Virtual Reality, Digital Twin, Big Data, Artificial Intelligence and Unmanned Ships. Each of these terms is frequently used and came with grand visions. In this paper, we look behind the high and mighty terms and see the sober reality behind. Often it is a case of false labelling or relabelling of more mundane, down-to-earth IT applications.

1. Introduction

We are living in a phase of 'digital transformation'. There is wide consensus on that, but beyond that, things become muddy and hazy. When did this phase start? How long do we expect it to last? And what is digital transformation, as opposed to digitization and digitalization? I suspect digital transformation is 'groovy', as nobody has been able to explain to me what exactly 'groovy' means either.

Most of us survive on poorly understood buzzwords, some of us thrive on them. If feeling disadvantaged, you may resort to agile internet-based tools in the industry 4.0 eco-system like https://www.makebullshit.com/. More advanced tools probably exist where you can feed in some keywords and out comes an impressive buzzword phrase. But your management may have beaten you to it already.

But often, it is also a case of taking a great idea, and starting by necessity on a much smaller scale. As in: "In the future, we shall boil the ocean, but as a proof-of-concept implementation of limited functionality, I will make a coffee." In other cases, marketing (including scientific self-marketing) has cleverly redefined goals to present success stories: "We define advanced calculus here as the ability to add two arbitrary positive one-digit numbers." Or intelligence as the ability to memorize 5 items, as in person, woman, man, camera, TV.

In the following, let's have a look at some of these new high and mighty terms and see how far reality lags behind the visions created when these buzzwords were originally coined.

2. Buzzwords or more?

2.1. Big Data

Enter the first buzzword: Big Data. Let's have a look at the definition of Big Data: "Big data is a field that treats […] data sets that are too large or complex to be dealt with by traditional data-processing application software." The COMPIT 2019 proceedings give 64 hits for the term "big data". On average, every 9 pages, someone used the term.

But most of the time, "much data" is meant when "Big Data" is used. As an example, we may collect automatic performance monitoring data from ships, and use some statistical analysis on those. 50 ships in our fleet, recording every 15 s a data set, each record consisting of 10 real numbers (speed, power, draft, trim, etc.). This makes some 1,000,000,000 numbers, or 4 GB in single precision. That can be transported on a plain USB stick and can be processed with standard software. It may take a while to open in Excel on a standard laptop, but reading and processing the data would be standard fare for a computer scientist. So, by definition, it shouldn't be called Big Data. You don't need distributed computers, working on subsets of the data to handle them at all, exchanging intermediate data to converge to a common result. As you would, for example, if it really were Big Data. Very likely, there are no Big Data applications in naval architecture and very few in shipbuilding and shipping.

In most cases, we have data-based analyses to derive information for decisions, Fig.1. But that sounds so mundane that one can understand the temptation to resort to the mighty "Big Data" incantation. I plead guilty to have fallen into that trap myself, *Krapp and Bertram (2016)*. Processing Gigabytes or even Terabytes of data does not in itself justify using the term Big Data, as we can process such amounts with conventional software and hardware. It may still be smart to use hierarchical data processing, especially when processing data from ship-board sensors before transmitting processed, and much more aggregated data via expensive internet channels to shore-based offices, but that is another story.

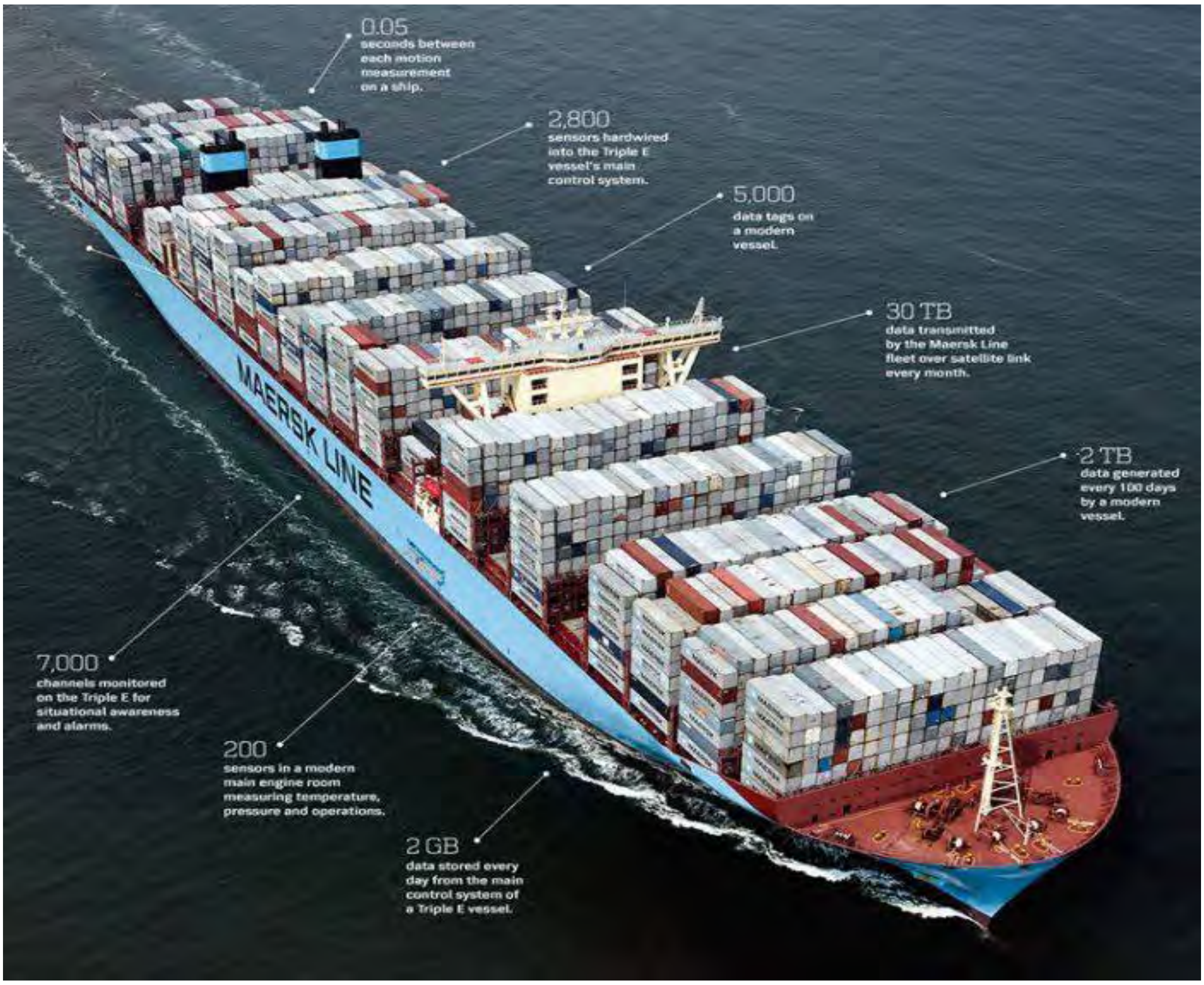

Fig.1: Processing Gigabytes or even Terabytes of data does not in itself mean "Big Data"

2.2. Artificial Intelligence

Another key buzzwords of our time is Artificial Intelligence, or A.I. as we really cool dudes call it. Alan Turing might be called the father of the concept of Artificial Intelligence, as he connected "computing" with "intelligence" in *Turing (1950)*. He proposed a machine (computer) that would converse so intelligently with humans that we wouldn't be able to tell whether it is a machine or a human. So far, all attempts to pass this Turing Test have failed. But it was John McCarthy, who coined the expression "Artificial Intelligence" in 1955, and the term was widely adopted and favored over other contenders (machine intelligence, thinking machines, cybernetics, automata theory, complex information processing) after the 1956 Dartmouth workshop. But even back then, A.I. experts couldn't exactly define A.I.

Wikipedia defines A.I. as "intelligence demonstrated by machines, unlike the natural intelligence displayed by humans and animals". The Oxford Dictionary defines A.I. as the development of computer systems able to "perform tasks normally requiring human intelligence". So, is it like human intelligence, or is it not? And what is human intelligence? Scientist still struggle with a clear definition of natural intelligence. But we have some common perceptions. Einstein was intelligent. And generally people who get Nobel prizes in physics must be very intelligent. So are top mathematicians, chess champions or world-class players of Go, a 2500 year old board game sometimes called the Chinese chess.

But in 2016, the computer program AlphaGo beat some high-ranking professional Go players. The event made the world news, not least because AlphaGo had learned "by itself", using artificial neural nets, a key technology of machine learning and thus A.I. In short, "self-taught A.I. computer beats best human", and it (he?) had learned the game from scratch within 40 days. So, did we witness the coming out of a super-intelligence that would in due time mean the end of mankind, as many Hollywood movies have suggested? Not really. If AlphaGo were our child, we would start worrying. Five years later, AlphaGo still hasn't shown any interest in learning anything else, say tic-tac-toe, or chess or Cluedo; it hasn't shown any signs of common sense or come up with any smart ideas, or whatever we would associate with an intelligent child. On a human I.Q. test, A.I. software generally fares catastrophically badly, getting scores around 40, where below 70 is a sign of mental retardation. Ask "Which animal goes moo?" and AlphaGo will give it a pass.

We could try to argue that it is "alternative" intelligence. And indeed, if we re-define what we consider intelligent as an impressive feat performed and beyond what the human mind can do, A.I. fits the bill. But so does traditional computing. Adding up 1 million numbers without making a mistake, within seconds. If we look at the biggest part of A.I., namely machine learning and its applications (including voice and pattern recognition), it used to be called "numerical statistics". That sounds immediately less groovy and less threatening than Artificial Intelligence, but you could put the A.I. sticker on any numerical statistics paper or application. Same thing, new label.

Numerical statistics is immensely powerful and, given enough and the right data, it can yield very powerful insight and enhance many applications in our field in the hands of intelligent engineers. Over the past two decades of COMPIT, I myself have presented many such possible applications, Fig.2, *Bertram (2000), Mesbahi and Bertram (2000), Bertram et al. (2016), Bertram and Herradon (2016)*, but we should see A.I. as a sober engineering tool and not expect true intelligence as in Einstein's out-of-the-box thinking from it. It is time to demystify A.I., *Bertram (2018).*

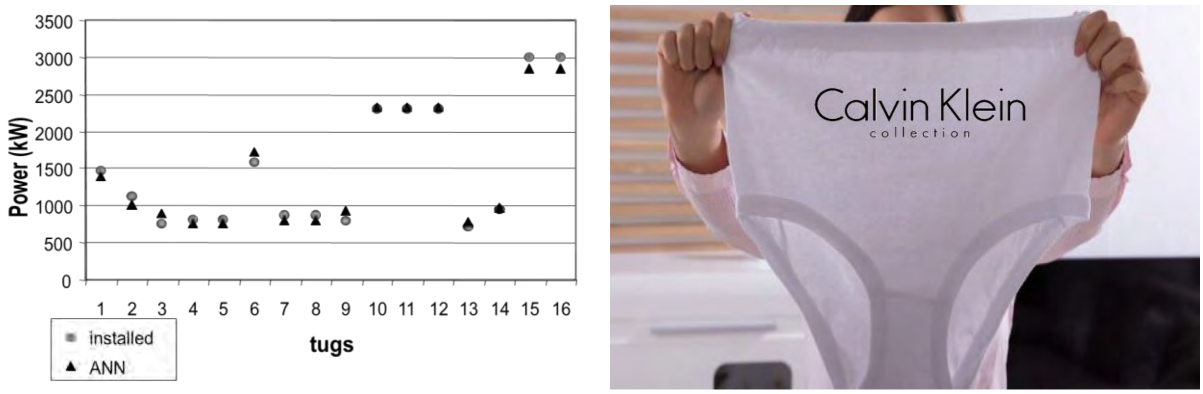

Fig.2: Artificial Intelligence is in most cases numerical statistics, immensely sensible like roomy underwear, but now with a sexier label

2.3. Unmanned ships

The vision of unmanned ships has been a recurrent theme at COMPIT for almost 20 years now, *Bertram (2003)*. But the whole theme really took off with an interview Oskar Levander (then Rolls-

Royce) gave to the Financial Times in December 2013. The story went viral on the Internet and in print media, and invoked visions of large-scale unmanned shipping being imminent, Fig.3: "According to Rolls-Royce Marine, by 2030 autonomous ships will be a common sight on the oceans," https://www.raconteur.net/technology/autonomous-ships/.

Fig.3: Vision of large-scale unmanned shipping by 2030, source: Rolls Royce

Fig.4: Likely reality, unmanned small ferries and tugs by 2030

Over time, not only ships got smarter, but also the maritime community. Most people now are more precise in their terminology, distinguishing between 'unmanned' (no crew on board, but under human command from a shore-based control centre) and 'autonomous' (controlled by software that acts independently, even if crew is on board; e.g. avoiding collisions if the crew does not act). While autonomous technology develops dynamically, the timelines and expectations for unmanned ships have sobered down significantly, e.g. *Bertram (2016)*, *Kooij and Hekkenberg (2019)*.

Unmanned ships need highly reliable systems on board, as there is no one on site to fix failures or perform maintenance. This is difficult to imagine with classical diesel propulsion with its many moving parts, even if cleaner fuels are used. In essence, the unmanned ship will be electrically powered. This makes the powering the limiting factor, rather than the information & communication technology. The key question is then: Can the ship take the kWh hurdle? How much power needs to be installed (mainly a matter of size and speed) and how far does the ship have to go before it can get recharged/refuelled. A containership with 50 MW power installed and a range of two weeks before refuelling would require excessive e-power and battery weight, Fig.4.

Even if we are much, much more modest, there remain significant hurdles to operating unmanned ships. The most advanced project today for unmanned cargo shipping is the 'MV Yara Birkeland'. The ship has a capacity of 120 TEU and a service speed of 6 kn; i.e. the vessel is very small and very slow for a containership. The longest route it is intended to sail is 30 nm, thus very short. All this lowers the kWh hurdle to a tiny fraction of what a 10000 TEU containership, sailing at 17 kn between Hamburg and Singapore would need. Still, the vessel is at 25 million USD an estimated 3 times as expensive as a conventional ship of the same size would cost. Without massive subsidies from the Norwegian government, it would not have been built. The subsidies can be justified as research funding and the technical achievements still command respect, but the kWh hurdles and economic hurdles remain.

By 2030, we will see unmanned ships in civilian applications, but mainly for short-distance ferries, tugs, fire-fighting boats, maybe offshore supply vessels. We will also see autonomous 'smart' systems on board many ships, supporting nautical tasks and cargo supervision, for example. But it will probably take another 20-30 years before we see wider adoption of international (e.g. transpacific) unmanned cargo shipping, *Bertram (2016)*. Another case where the vision is far ahead of reality.

2.4. Digital Twin

Enter the ‘Digital Twin’, another recent favourite of COMPIT papers, used 178 times in the 2019 proceedings. Wikipedia defines a Digital Twin as “a real-time digital replica of a physical device”. Siemens elaborates on this to give “a smart (dynamic), virtual representation (model) of the physical product, production process, or product's utilization. It has the required accuracy and fidelity to predict actual, physical performance”, Fig.5. In simple terms, the vision was some IT model with the look and feel of the real deal. Not only would it look like its physical twin (this would be mere Computer-Generated Imagery or Virtual Reality), but it would behave like its physical twin and evolve in time like it. The Digital Twin of a ship would lose strength in time as it rusts, slow down as the hull gets fouled, vibrate according to the propeller and engine excitation, etc.

Fig.5: Digital Twin vision

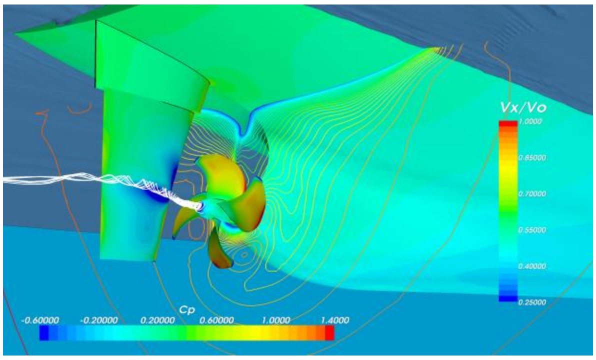

Fig.6: Typical hydrodynamic simulation model

Industry reality is much less ambitious. We now use the term “Digital Twin” where some years ago we would have used “simulation”, e.g. *Bertram (2004), Peric and Bertram (2011), Bertram and Peric (2013)*. Digital model (for simulation) would be much more appropriate as a term, *Cabos and Rostock (2018)*. The discrepancy between vision and reality is so large that one could speak of false labelling:

- Most often, ‘Digital Twins’ model geometrically only a small part of the real counterpart, e.g. only the underwater hull and propeller for hydrodynamic simulations, Fig.6.
- Most often, ‘Digital Twins’ simulate only one specific behaviour, e.g. calm-water propulsion, seakeeping in waves, static strength of steel structure, vibration of structure, etc. For each application, another model is needed due to different requirements of the numerical methods and different purposes of the simulations.
- Most often, ‘Digital Twins’ do not evolve in time. Instead, now we see expressions such as ‘design Digital Twin’ or ‘production Digital Twin’, indicating that this twin will expire once its real counterpart is delivered to the ship owner.

2.5. Virtual Reality

The term ‘Virtual Reality’ was coined by Jaron Lanier in the late 1980s. His vision for fully immersive Virtual Reality (VR) was a digital technology that allowed users to experience artificial environments as the real world, to the point where the difference between the virtual world and the real world could no longer be realised. You see, you hear, you smell, you taste, you feel. In short, the vision was akin to the Holodeck in Star Trek, the Holy Grail of the Virtual Reality community. You get kicked and your ribs break – and you hear the crack and you hurt, Fig.7.

Beier (2000) described in the first COMPIT conference how this grand vision got reduced to something much more modest and tangible, namely a 3D computer model with walk-around capabilities: “The term Virtual Reality initially referred to [… fully] immersive systems. With time, the meaning of VR broadened and, as of today, VR is also being used for semi-immersive systems, […] even non-immersive systems, like monitor-based viewing of three-dimensional objects.”

Fig.7: The Holy Grail of VR: The Holodeck; you get kicked, your ribs break

Fig.8: Current reality, (maybe) 3D viewing & walk-around with some high-res graphics

The down-to-earth VR is useful for many applications in our industry, mainly in understanding and selling designs to training and marketing, Figs.9 and 10. Many papers in 20 years of COMPIT bear witness to that. But if we take a closer look at how much VR is really used in industry, beyond the smoke screen of marketing appearances and feasibility studies, the uptake of the technology, even in its much more mundane re-definition, is sobering for any VR afficionado, *Bertram and Plowman (2018)*. The vision is still far ahead of reality.

Fig.9: Training application of VR

Fig.10: Marketing application of VR, source: Lloyd's Register

2.6. Other

But wait, there is more to come… Marketing is always ahead of the game and the engineers and programmers in the R&D departments. Just a few examples shall be given:

- 3D printing (additive manufacturing) came with grand visions. "The ONR (Office of Naval Research) of the US Navy published a report to explore the possibility of producing the whole ship using 3D printing," in *Matsuo (2018)*. Possibly you could, but would it yield ship structures of same strength at lower prices than current welding technology? The maritime applications so far are for structures with low strength requirements, such as boats, Fig.11, where fibre-reinforced plastics and wood are also options.

  The best arguments for 3D printing in the maritime industry are for spare parts of limited lifetime, where a broken part in some machinery can be 3D printed on board as a quick repair to continue operation. As a marketing gadget or as scaled-down model for discussion with customers, 3D printing may come in handy, Fig.12, *Koelman (2013)*. Afficionados of a technology focus on what is feasible, not what makes economic sense. And even the 3D printing afficionados admit "that the vision of 3D printing an entire ship is (still) somewhat into the future," *NN (2017)*.

Fig.11: 3D printed boat

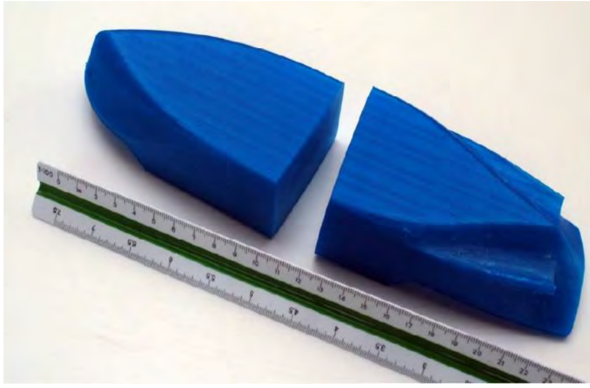

Fig.12: 3D printed demo model, Source: SARC

- Enter Industry 4.0. "Industry 4.0 refers to the transformation of industry through the intelligent networking of machines and processes with the help of information and communication technology (ICT). The term is used interchangeably with the 'fourth industrial revolution' in industry," https://www.i-scoop.eu/industry-4-0/. Which sounds good, except that at least in the maritime industry the factories (shipyards) are mostly too small to recover the required investment into further robotization and the unfortunate policies of closed data formats creates interfacing barriers, *Danese and Vannas (2020)*. Fast internet connections of 'things' are fairly useless, unless the 'things' can communicate in a common language to exchange information. We have promising ideas, but they will take time to enter the industry and take hold in daily practice. The vision is once again far ahead…

- Enter PLM. "In industry, product lifecycle management (PLM) is the process of managing the entire lifecycle of a product from inception, through engineering design and manufacture, to service and disposal of manufactured products," Wikipedia. Of course, this can be synchronised in an agile solution, etc. But apart from the mandatory inventory of hazardous materials (IHM), the reality is that a ship has at least two lives in terms of product data models: It grows from inception (= concept design) to manufacture (= shipyard assembly) and then dies, with a minimum of information passed on to the customer (= ship owner), often in the form of paper. During service (=operation), we may see occasional creation of new island solutions for product models, but these most often also die when the ship is passed on to a charterer or sold to the next owner. But if we redefine 'disposal' as meaning 'delivery' by the shipyard, we have some nice PLM solutions on the market.

I am sure that the list could be continued with many more examples of where we have boastful claims and visions far ahead of industry reality. As I have benefitted from the collective and sometimes acerbic wisdom of the COMPIT community, I will continue to do so with the response to this paper.

3. Conclusions

The glass is half full or the glass is half empty. All technologies discussed have progressed in the past 20 years, and often we have also progressed towards a realistic understanding of what is (at present) meant by a certain buzzword, what it can do, and what its limitations are. Realistically, we should also be resigned to the use of more new buzzwords for concepts that have been around for a long time, and to marketing departments promising us far more than production can actually deliver. Let's be grateful for the occasional contribution to this conference that takes a sceptical point of view and is not fooled by the misuse of widely accepted buzzwords.

Acknowledgements

Over the years, by now two decades, I have taken much inspiration from COMPIT, to the point where I can no longer remember clearly who had this or that idea first. I know that some of the ideas in this

paper and even some of the formulations are not originally mine, but have come from the wonderful COMPIT community. If I have been guilty of idea socialism (a much nicer word than theft), I beg your indulgence, whoever had the idea first. Nick Danese and Herbert Koelman are the most likely usual suspects. Thanks to all those referenced below.

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Robotic Hull Cleaning – Past, Present and Prospects

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Abstract

This paper describes the development of robotic hull cleaning from academic research in the 1980s to current industry standard, including potential paths for further development towards mass-produced, standardized robotic designs with more advanced capabilities.

1. Introduction

In the quest for more sustainable hull management strategies for the future, some of the most promising contenders involve frequent 'pro-active cleaning' or 'grooming' to remove the biofouling at an early stage, e.g. *Oftedahl and Enström (2020)*, *Hunsucker et al. (2018), Swain et al. (2020)*. "Frequent" may mean every two weeks, to give an idea. Such frequent cleaning would remove biofilms before advanced calcareous fouling can develop, addressing issues of aquatic invasive species and energy efficiency at the same time. In order to be widely available and affordable, such proactive cleaning would have to be largely robotic.

The required technologies have been coming together, recently maturing to commercial applications. Perhaps the appearance of a dedicated Wikipedia site on in-water cleaning can be seen as a sign of the generally larger interest in the theme: https://en.wikipedia.org/wiki/In-water_surface_cleaning. We may be at the dawn of a new era of mechanical cleaning (by robots), *Bertram (2020)*.

2. Diversity and fragmentation in a young industry

In-water cleaning robots come in a large variety of designs/concepts and are usually one-of-a-kind productions. This fragmented approach with its lack of standardization is typical for young industries. (Most of the developments started within the last decade). *Noordstrand (2020)* discusses the typical issues of young industries that are currently afflicting the in-water robotic cleaning market.

The current state of the industry with its design diversity is due to various reasons:

- The appropriate cleaning approach depends on the paint coating used on the hull, which ranges from soft dissolving self-polishing copolymer paints, mechanically sensitive foul release coatings, to hard varnishes.
- The in-water cleaning industry is highly fragmented and relatively small in total volume. The market leader for robotic in-water cleaning, HullWiper, is at best a small-to-medium enterprise with less than 50 employees.
- Cleaning companies develop their own designs and build or have them built in near-by workshops, in a "do-it-yourself" style typical for young industries. (Think of how the first automobiles or PCs were designed and built in private garages.)
- There are no standards yet for the design or production of such robots.

With time, we should see some consolidation of the market and robot designs as we did for other industries (automotive, airplanes, PCs, …).

Eventually, we may see dedicated manufacturers of in-water cleaning robots supplying the service providers with mass produced or at least mini-series produced robots, possibly with modular design approaches to allow the necessary flexibility while maintaining low-cost production. We will also see robot design move from "do-it-yourself" assembly design to more professional approaches, using computer-aided design including hydrodynamic optimization, as indicated by *Lee et al. (2012).*

3. Past, present and prospects

3.1. Past – The academic research era

Research into hull cleaning robots probably started in the 1990s. *Bertram (2000)* mentions some research projects. The robots of the time were bulky do-it-yourself assemblies from academic research laboratories, Fig.1. Several EU projects advanced robotic inspection and cleaning technology, e.g. the AURORA project, Fig.2, *Armada et al. (2004)*. However, while these efforts prepared the ground for today's state-of-the-art, they remained research focussed and did not directly translate into industrial applications.

Fig.1: Cleaning robot of Hiroshima University, *Bertram (2000)*

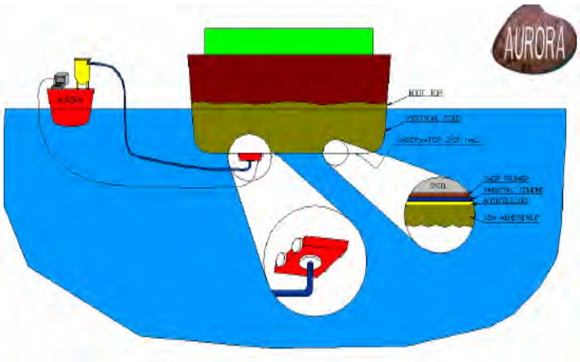

Fig.2: AURORA cleaning robot, *Armada et al. (2004)*

3.2. Present – The start-up and adapt era

This overview draws on previous surveys which are highly recommended for more in-depth information, namely *Souto et al. (2015), Albitar et al. (2016), Curran et al. (2016), Song and Cui (2020)*. Table I lists current in-water cleaning robotic solutions. Within 5 years, for a third of the robotic solutions listed in *Curran et al. (2016),* there were no longer supported websites or more recent publications, suggesting that these would-be contenders had left the market. There are fewer new entries than drop-outs. This is partly due to Table I listing only commercial solutions, partly due to the still volatile market where start-ups disappear or are absorbed in merger & acquisitions.

Table I: Overview of commercial in-water robotic cleaning solutions

Robot	Country	Adhesion system	Cleaning system
COLLECTOR	Norway	Magnetic	Waterjet
Daewon robot	Korea	Thrusters	Brush
Fleet Cleaner	NL	Magnetic	Waterjet
Hullbot	Australia	Thrusters	Brush
Hull BUG	USA	Magnetic/Vacuum	Brush/Waterjet
Hull Cleaner	USA	Magnetic	Brush/Ultrasonic
HullSkater	Norway	Magnetic	Brush
Hull Surface Treatment	Australia	Magnetic	Thermal shock
HullWiper	UAE	Vacuum	Waterjet
KeelCrab	Italy	Vacuum	Brush
Vertidrive M-series	NL	Magnetic	Waterjet
Magnetic Hull Crawler	France	Magnetic	Waterjet
Magnetic crawler	USA	Magnetic	Ultrasonic
Rovingbat	France	Vacuum	Brush/Waterjet
ITCH	Norway	Ship flow field	Brush

There are many ways to categorize in-water cleaning robots, including:

- Cleaning technology (brushes, high-pressure or cavitational waterjets, laser, …)
- Adhesion technology (magnetic, vacuum (negative pressure), thrusters, …)
- Level of autonomy (diver controlled, remotely controlled, more or less autonomous)
- Region/country (USA, Europe, Japan, …)
- Market (pleasure boats, commercial ships, navies, …)
- …

Most systems on the market today favour magnetic adhesion, making them unsuitable for aluminium, reinforced plastics and wooden hulls commonly found in the pleasure craft industry. Vacuum (= negative pressure) adhesion is also popular, while use of thrust force, e.g. *Ishii et al. (2014)*, *Souto et al. (2015),* or adhesive elastomer materials in research applications is rather exotic, *Song and Cui (2020)*. Adhesion by flow forces of the moving ship is only applicable for largely flat sides, not the ship ends and the ship bottom, *Freyer and Eide (2020)*.

Rotary brushes and waterjets are commonly used, with waterjets taking a more prominent role in the most recent developments. This shouldn't come as a surprise, as the concept of gentler and more frequent cleaning in itself has been accepted by a wider public only recently. Ultrasonic technology and laser cleaning technology have been proposed by various researchers, but do not play a significant role in industry practice, *Song and Cui (2020).* (Note that ultrasonic antifouling protection in stationary installations for niche areas and internal pipes has gained in popularity, e.g. *Kelling (2020),* but use of the technology in underwater robots is rare.) *Akinfiev et al. (2007), Morrisey and Woods (2015)*, *Song and Cui (2020)* give more in-depth discussions of cleaning technologies.

3.2.1. Key players for commercial applications

Several companies have defined the state of the art through pioneering developments and presentations at professional events like HullPIC and PortPIC:

- HullWiper, www.hullwiper.co, is the market leader in terms of size (employees and probably turnover) and ports served (10 ports in late 2020, with 3 more planned for 2021). The Hull-Wiper robot, Fig.3, *Doran (2019,2020)*, "collects marine fouling removed from hulls, rather than polluting local port water and risking the spread of harmful invasive species. Captured residues are pumped into a filter unit and then deposited into dedicated drums onshore, which are collected by a [locally approved] environmental waste disposal company. [… The robot] sprays adjustable high-pressure seawater jets directly onto a ship's hull at a very high velocity to dislodge waste materials, without using scrubbing, harsh chemicals or abrasive materials required for traditional methods. […] The use of high-pressure jets for cleaning ensures that HullWiper does not damage the ship's […] antifouling coatings." The robot is relatively large (3.3 m (L) x 1.7 m (W) x 0.85 m (H)) and heavy (1275 kg).

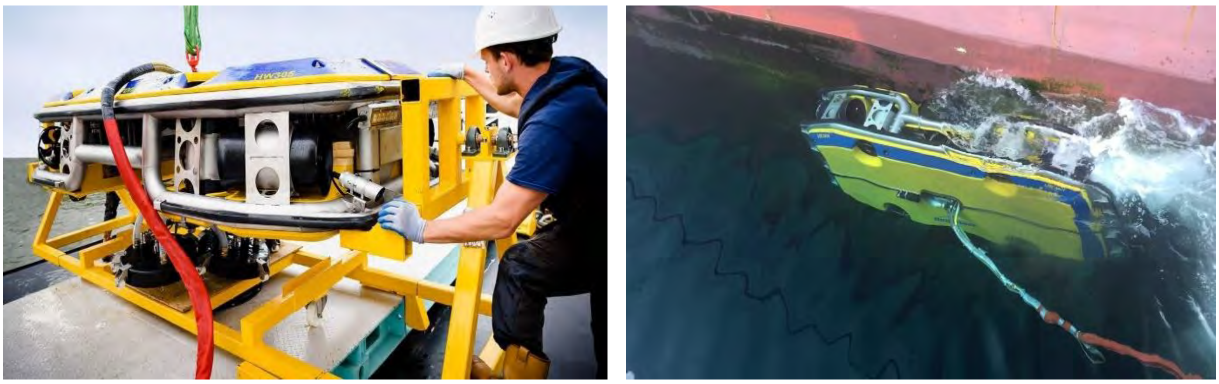

Fig.3: HullWiper robot, www.hullwiper.co

- Fleet Cleaner, www.fleetcleaner.com, has developed its robotic cleaning solution since 2011, with first field trials in 2016, *Noordstrand (2018)*. In subsequent years, the service was extended to all Dutch ports and eventually also to Belgian ports, *Cornelis et al. (2020)*. The self-developed robot uses magnetic attachment and cleans with high-pressure waterjets. The design is relatively compact (2.0 m (L) x 1.8 m (W) x 0.6 m (H)). Cleaning a ship typically takes 10 h with the latest technology. Like the HullWiper robot, the Fleet Cleaner robot collects the removed debris for proper disposal.

Fig.4: Fleet Cleaner robot, www.fleetcleaner.com

- ECOsubsea, www.ecobsubsea.com, started in 2008 in Norway, but has its main operational base in Southampton. Its robot 'Collector', Fig.5, uses magnetic adhesion, waterjet cleaning and collects the debris, citing "more than 97.5%" as its collection rate. The 'Collector' is a similar size to the HullWiper (3.0 m (L) x 2.0 m (W) x 0.7 m (H)), but is considerably lighter (715 kg). Cleaning a ship takes typically 5 h. The collected debris is properly disposed of and serves to generate biogas. The service is offered in 19 ports according to the company's website, Fig.6, mainly covering North Sea and Baltic ports.

Fig.5: 'Collector' robot

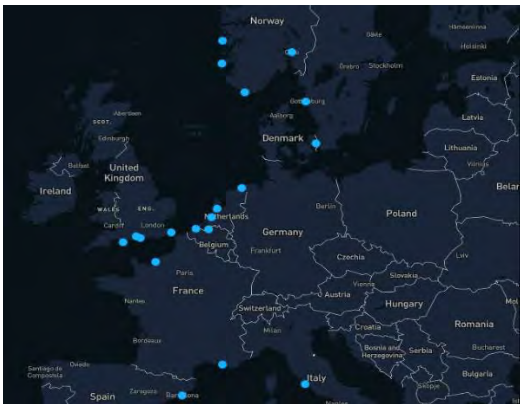

Fig.6: Ports served by ECOsubsea

- SeaRobotics, www.searobotics.com, developed the 'Hull BUG' (BUG = bioinspired underwater grooming) funded by the Office of Naval Research in the USA, Fig.7, *Schütz (2012)*. The robot uses vacuum suction for adhesion and brushes to remove biofilm. It is designed for autonomous operation, like a robotic lawnmower or pool cleaner. Onboard sensors allow it to steer around obstacles, and a fluorometer enables it to detect biofilm to be removed. The robot is relatively small (1.5 m (L) x 0.75 m (W) x 0.75 cm (H)) and light (55 kg). This makes it easier to cope with curved parts of the ship. SeaRobotics has continued the development with the SR-HullBUG, Fig.8, which is larger (1.5 m (L) x 1.1 m (W) x 0.75 cm (H)) and heavier (370 kg). It has changeable grooming or cleaning tools, listing cavitational waterjet tools explicitly. As the SR-HullBUG addresses cleaning at the biofilm stage, before macro-fouling can develop, there is no need to collect the removed fouling.

Fig.7: Hull BUG

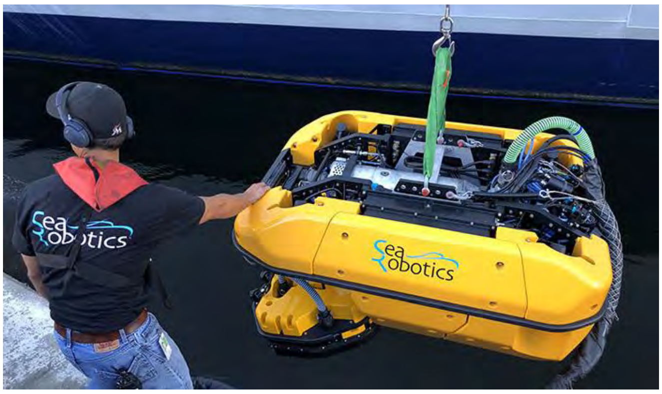

Fig.8: SR-HullBUG

- Jotun, https://jointherevhullution.com, launched its HSS (Hull Skating Solutions) in 2020, Fig.9, which was developed in partnership with Kongsberg, Semcon, Telenor, DNV GL and Wallenius Wilhemsen. The Hull Skater robot uses magnetic adhesion and soft brush cleaning. As it is only intended to remove biofilm, there is no need to collect debris. The Hull Skater robot, https://octagavs.com/JotunHSS_mobile/, travels on-board with the ship, and is launched and retrieved by the crew. The inspection and cleaning missions are remotely controlled by Jotun. During inspection, the robot identifies areas of advanced fouling, which are not cleaned by the robot and are subject to later cleaning by other means allowing collection of removed advanced fouling to prevent spread of aquatic invasive species. The Hull Skater is relatively small (1.6 m (L) x 1.0 m (W) x ~0.5 m (H)) and light-weight (200 kg), https://semcon.com/uk/jotunhullskater/. Cleaning a (150 m) ship typically takes 4-5 h.

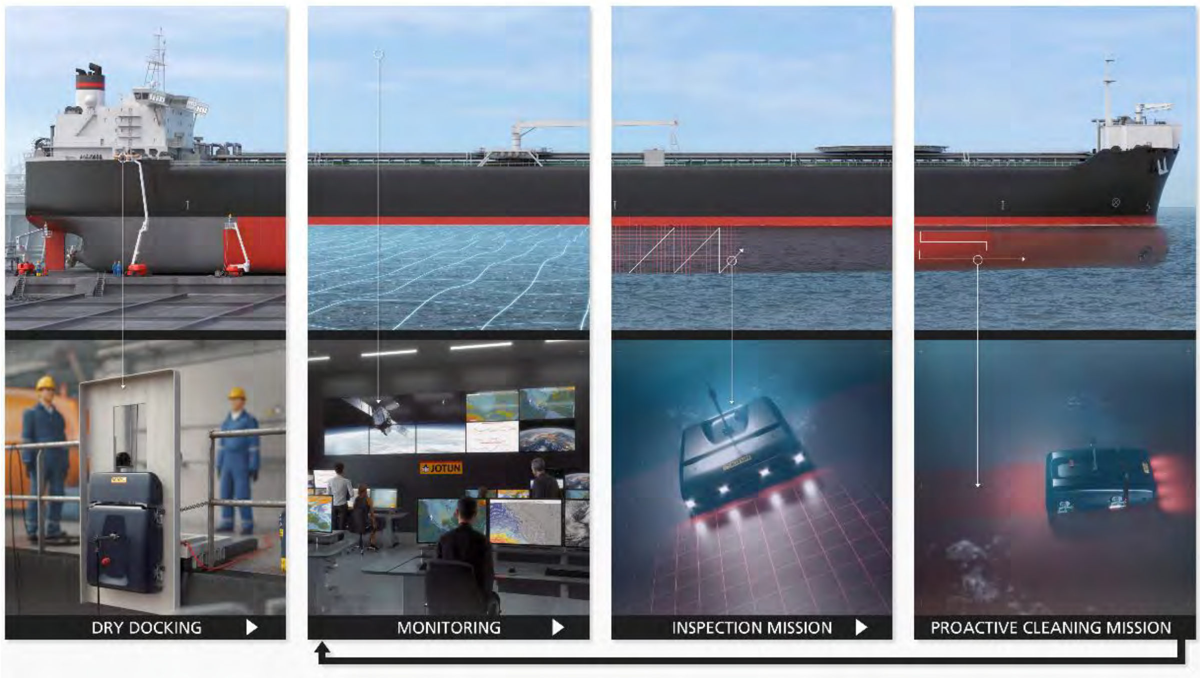

Fig.9: Hull Skating Solutions with (from left to right) robot launched by crew; performance monitoring and remote control of robot by Jotun experts; inspection mode to identify no-go areas with fouling beyond biofilm; and subsequent cleaning of biofilm

3.2.2. Flanking measures

Besides the technical and economic development of in-water cleaning robots, there are additional measures needed to develop the 'eco-system' of in-water, in-port cleaning:

- Guidelines are needed for various aspects, such as accreditation for in-port cleaning, matching of cleaning method and coating, collection and disposal of removed fouling, documentation of cleaning results, etc. E.g. *Oftedahl and Enström (2020), Sørensen (2020*), the NACE TG 581 on NACE's Standard Practice 'Inspecting and Reporting Biofouling and Antifouling System Condition during an Underwater Survey', and several proposals for the due update of IMO's 'Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species' are such useful contributions benefitting the industry at large.
- Ports need to adapt policies to the changing technologies of coating and cleaning, requiring adequate proof of environmentally acceptable procedures, but also allowing in-port cleaning if required documentation can be given by service providers. E.g. Belgian ports, *Cornelis et al. (2020)*, set a good example in this respect. Policies should be aligned at least within regions, to avoid the "wild west" of unaligned and unregulated practices rightfully lamented by *Noord-strand (2020)*.

3.3. Prospects

"Prediction is very difficult, especially about the future", as Nobel laureate Niels Bohr so wisely said. Still, we can look at recent research and development and may speculate on what may come:

- Team capability in cleaning robots – Cooperative robotics is one of the major research areas within the robotics community. The basic idea is to have two or more robots working as a team on a task. In the maritime field, there have been some applications of such cooperative robotics, e.g. for mapping of seabed, establishing towline connections, or search/patrolling tasks, e.g. *Odetti et al. (2016), Lewis (2017).* For hull cleaning, cooperative robotics would allow parallelization of work and thus much shorter cleaning times. One could also imagine smaller robots focussing on areas of high curvature, while a larger robot is used for large flat areas. The technology of robot location, ship surface mapping, and communication between robots (and possibly a central surface control centre) is available, we "just" need to get the robotics community and the hull cleaning industry connected. It seems a perfect opportunity for an EU project.

- System solutions – Mismatching coating solution, cleaning technology and procedures has led to frequent problems and finger-pointing between the various stakeholders. While we often hear the mantra that cleaning and coating should be matched properly, a multitude of products/services coming from a multitude of changing suppliers seems like a recipe for failure. We need system solutions, at least in the form of clear instructions for cleaning coming from the coating suppliers and procedures that ensure that these instructions were received and understood by the cleaning providers. Information loss between stakeholders is best avoided by integrated solutions. Jotun's Hull Skating Solutions, *Oftedahl and Enström (2020)*, are a role model that hopefully will inspire larger parts of the industry to follow. Here, coating, robotic cleaning, performance monitoring (to trigger the cleaning and monitor the effect on performance) and contractual warranties come under one umbrella.

- Port services or on-board equipment – Most robotic cleaning solutions assume a dedicated service provider, providing the robot and the cleaning service in certain (and, so far, few) ports. Exceptions to this rule have appeared in 2020 with Jotun's hull skating solutions and Shipshave's ITCH (In Transit Cleaning of Hulls) semi-autonomous robot. Both are launched and retrieved by the ship's crew, travel with the ship and are thus independent of available port infrastructure. On-board cleaning robots overcome the issue of scarce port services. In-port services have the advantage that equipment is utilized over many ships, with the associated economies of scale. In the long term, say over a decade or two, these economies of scale may favour in-port service providers, echoing a similar development away from multi-purpose ships (with their under-utilized on-board cargo handling equipment) towards containerships (relying on port-side services), but this requires wider deployment of port-side robotic cleaning solutions which I am confident we will see, but which will take time. In the meantime, we may see more rapid growth of on-board solutions.

4. Conclusion

Robotic in-water cleaning technology has come a long way from early research attempts to the current state of the art. We are currently in a steep part of the learning curve and the rapid evolution of this still young industry. Technology, regulatory frameworks and procedural guidelines, as well as markets, are developing dynamically. Teething problems and occasional setbacks (or learning moments) are to be expected, but the future looks rather bright for this particular segment of the maritime world.

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Direct Integration of 3D Laser Scanning in CAD

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This paper describes our experience with incorporating 3D laser scans directly in maritime CAD environments. The prime application is for retrofit projects where the current technology saves time and money and allows rapid, intuitive visualization vital during retrofit projects. The technology can cut 35% in material costs and 25% in installation time in retrofit projects.

1. Introduction

1.1. The need for 3D capturing in the maritime world

The Digital Twin concept has evolved to one of the big IT buzzwords in the engineering world, including the maritime industries. Numerous papers give testimony of this, e.g. *Cabos and Rostock (2018)* and *Erikstad (2018)*. At the core of any Digital Twin will be a 3D geometrical representation, which then in turn opens the door for numerous applications in simulating physical behaviour and Virtual Reality interaction. As such, this is old hat, *Aarnio (2000)*. But how do we get a 3D model and how do we ensure that the Digital Twin evolves as its physical counterpart?

For the steel hull, we may use thickness measurement campaigns to update the Digital Twin, at least for the changing hull thickness, *Jaramillo and Cabos (2006)*.

For hull geometry, *Bole (2014)* discussed 3D ship hull scans to be imported to (re)-design software, namely the Aveva design world. Here, smooth CAD surfaces are fitted to the (coarsely) scanned ship hull. But such applications have been out as falling short of what is needed for some purposes. E.g. the as-built hull geometry including welds and appendages like bilge keels may need to be scanned with high resolution to support CFD power predictions of as-built ships to reduce uncertainties, *Bertram (2020)*; using as-designed CAD geometries cannot reflect variations in sea trial measurements for sister vessels which may be in excess of 5.5%, *Krapp and Bertram (2016)*. Updating the hull geometry including changing marine fouling and degrading hull roughness using 3D laser scan technology has been discussed recently, *Paranhos (2020)*. The demand is there, but the state of the art has not yet drifted into industry practice.

For equipment and internal arrangement, the situation is considerably worse. Designs are frequently ignored or changed ad-hoc in the outfitting phase, and retrofitted equipment is often not reflected in the (supposed) Digital Twin model, e.g. of an engine room. This became blatantly apparent in recent years, when IMO regulations forced many ship owners to retrofit ballast water treatment systems (BWTS) and exhaust gas cleaning systems (EGCS) (= ‘scrubbers’). Similar issues appear when considering retrofitting energy saving equipment, e.g. exhaust heat recovery systems.

The available resolution of 3D laser scanning has increased, while cost and portability of 3D scanners have decreased. As often in IT applications, a key issue is the interfacing between different software solutions and the art of creating not just a (3D scan) model, but creating it efficiently and to the appropriate level of detail needed for the customer’s purpose.

1.2. How Blom Maritime addresses this need

Blom Maritime is a part of the TECO Maritime Group, with focus on marine engineering and naval architecture. Our team consists of project managers, naval architects, piping engineers, structural engineers, surveyors and data analysts, as needed to support our multidisciplinary projects. We specialize in capturing and optimizing “as-is” data for improved engineering and project execution. In fact, Blom Maritime is the world leading supplier of 3D digital data capturing.

Linking high-resolution 3D scanned point clouds into the maritime CAD world of our customers and partners requires are suite of software products. In our daily work, we connect to software from AVEVA, ANSYS, Autodesk, Bentley, Rhino, and Leica, Fig.1.

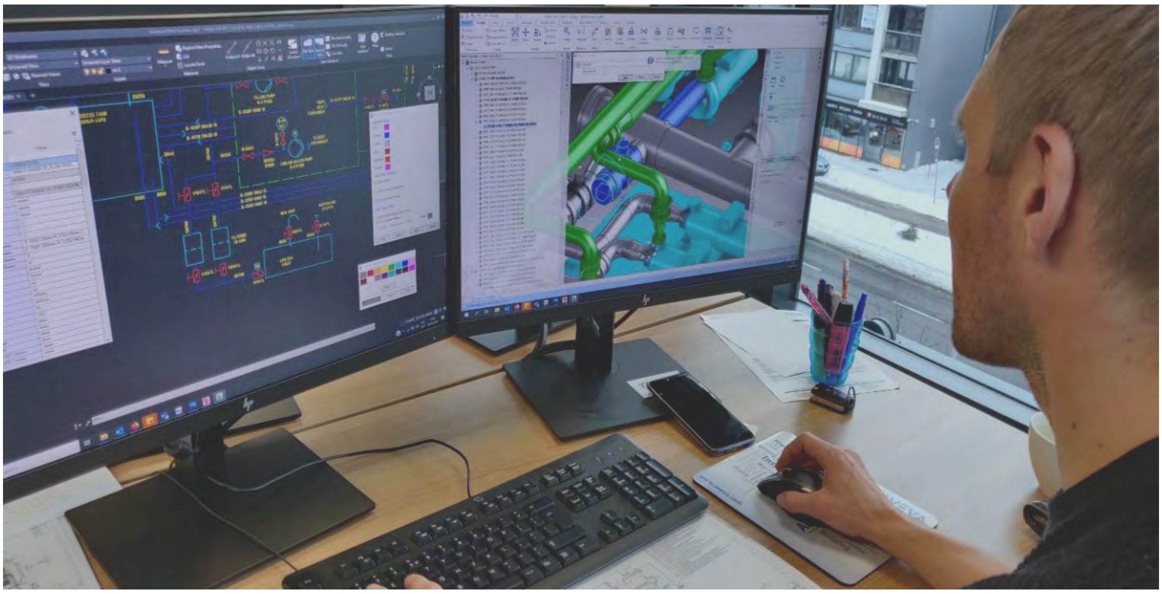


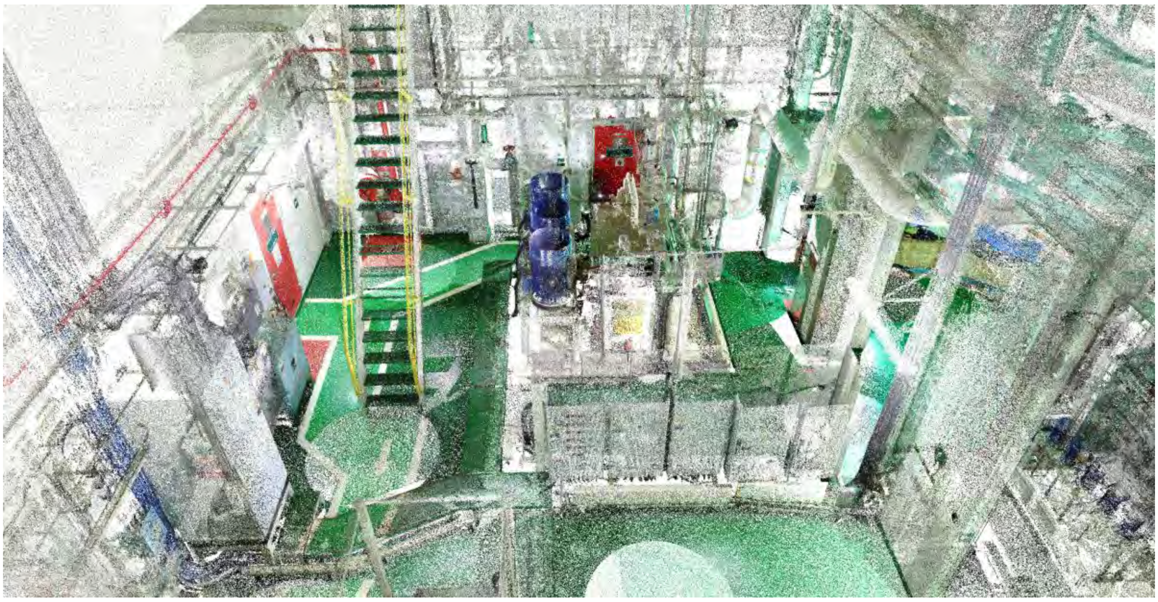
Fig.1: Our team connects high-res 3D scanned point clouds with popular maritime CAD software.

2. Applications combining 3D scanning, design & operation of ships

The high-resolution 3D scan results in a point cloud that can be integrated in CAD and VR (Virtual reality) software for a multitude of industry applications, as briefly outlined below.

2.1. Survey and 3D Laser scanning

- Retrofit surveys
- 3D laser scanning
- Virtual representation
- Cloud data with an accuracy of ±2 mm is achieved.
- No interruption to the assets' operations, while scanning, Fig.2



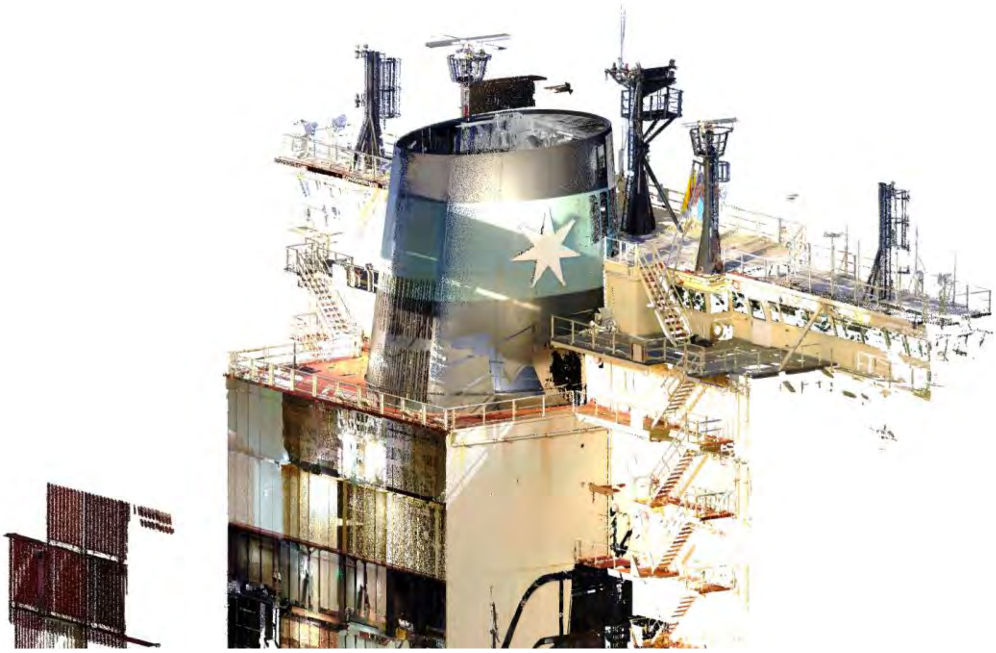


Fig.2: Assets can be scanned while in usual operation (top) and the resulting scan (bottom) is the starting point for further engineering application.

2.2. 3D conceptual (re-)design

- Conceptual design
- Virtual merging existing systems with new design
- Alternative solutions discussed
- Multiple systems could be modelled to verify their suitability on board
- Conceptual design freeze

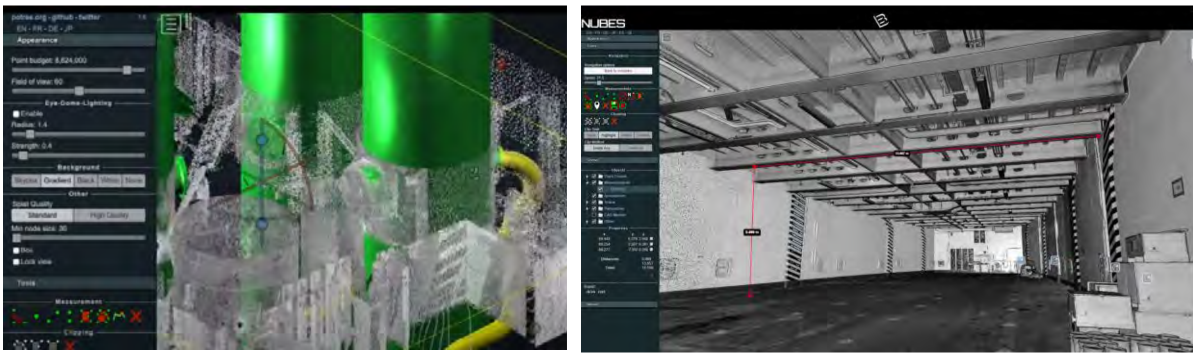


Fig.3: Concept design fitted to point-cloud presentation (left), measurements in point-cloud by using NUBES inhouse software.

2.3. Detailed design

- Multi-disciplinary concurrent engineering
- Pipe, Structure and electrical design, Figs.4 and 5
- ISO and Updated CAD drawings
- Flow/Stress calculations
- Drawings &documents
- Design validation
- Material takeoff

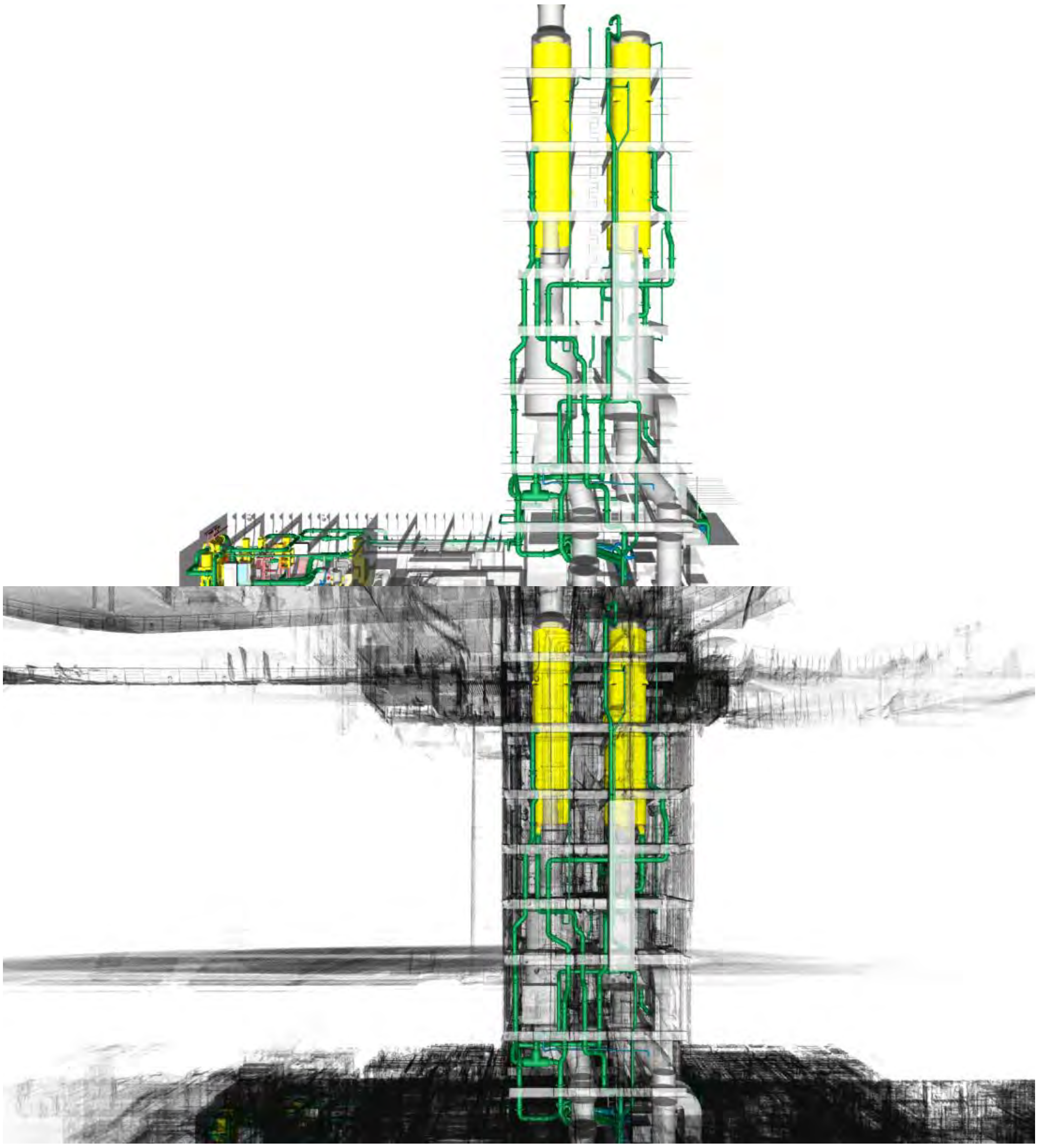


Fig.4: CAD design (Top) and point-clouds can be directly merged (Bottom) without having to recreate CAD surfaces.

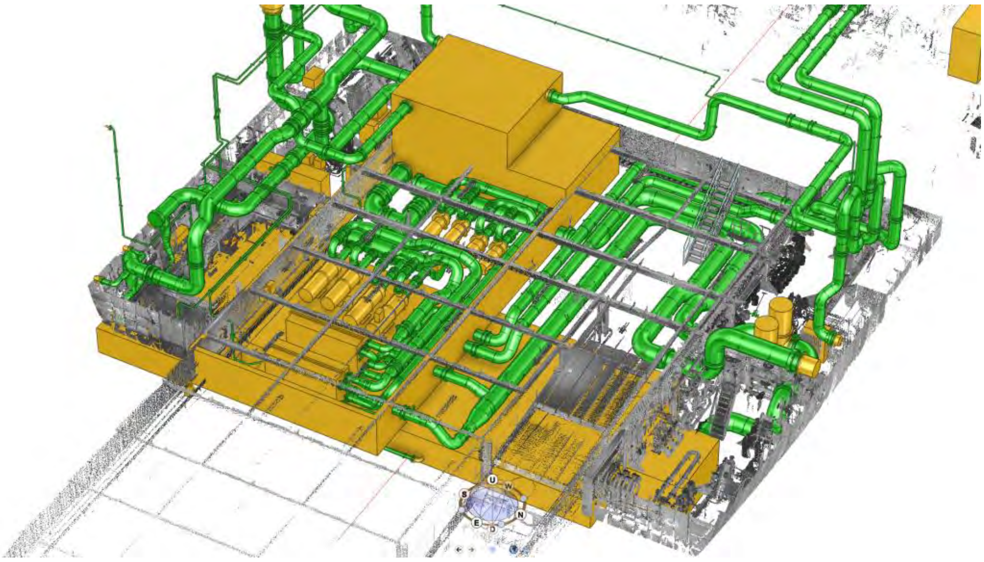


Fig.5: Detail design from AVEVA software created according to as-is point-cloud.

2.4. Class approval

- All deliverables submitted to class authorities
- Criteria of class rules are followed while design
- Minimal changes to deliverables after class comments
- Class comments are addressed diligently
- Smooth class approval process
- Class approval process will go on till Installation and commissioning phase

Fig.6: Example of class approval organizations.

2.5. NUBES

This in-house interactive virtual platform allows clients to check the custom design in the scanned digital twin from their own office. It is a vital tool for visualizing the design and showing clients exactly what will be installed. The intuitive visualization solution reduces risk, installation time, and make sure there are no surprises. The platform supports multi-user access and Virtual Reality (VR) viewing, from all major web browsers. The data is secured with security certificates and a unique password for each user for easy access.

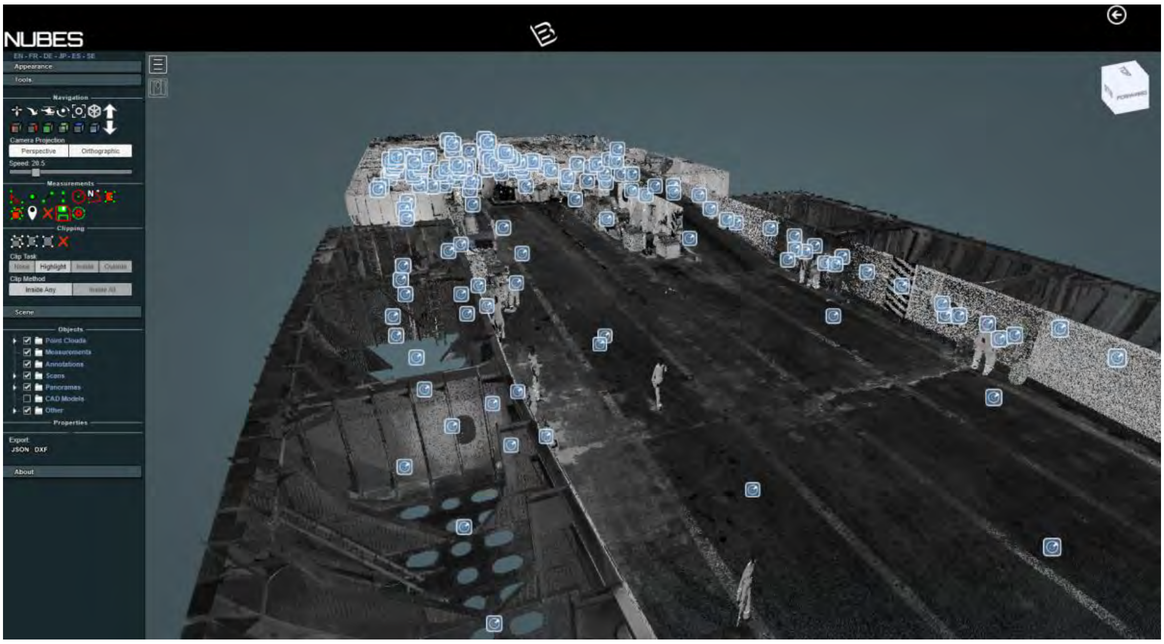


Fig.7: NUBES interactive virtual platform.

3. Conclusions

Maritime environmental regulations have led to a surge in retrofits, e.g. with scrubbers and ballast water treatment systems. For older ships without appropriate digital representation of the as-built status, this can be a major headache. 3D Laser Scanning has been found to be a viable solution for such cases. Initially motivated for retrofits, the geometrical digital twin created by advanced 3D laser scanning has been found to be very versatile, being used e.g. also for preventive maintenance or further redesign of engine rooms. In our experience, "data at your fingertips" have saved up to 30% on material cost and up to 35% on manhours in retrofit projects.

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Digital Maritime Training Supported by Biometrical Measurement

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Abstract

This paper presents a design for measuring biometric markers in the full-mission simulator during collision avoidance simulation. The additional source of information in digitized maritime training is the quantification of trainee's performance by observing biometric markers, e.g., heart rate, blood volume pulse, and electro-dermal activity. The rate of change of the measured variables indirectly provides information about the state of the participant's working memory process at a particular stage of maritime training. The biometric behaviour in combination with the self-assessment provides information about the degree of cognitive load affecting the individual's performance.

1. Introduction

The primary objective of this work is to investigate the usefulness of participants' biometric parameters recorded in the ship's bridge simulator during training of collision avoidance manoeuver. Despite state-of-the-art electronic navigation devices, including augmented reality assisted, *Procee et al. (2017)*, integrated into a modern ship's bridge, the Officer on Watch (OOW) remains responsible for making final decisions and continues to bear the responsibility for navigational safety. As the analysis of maritime accidents reveals, *EMSA (2020)*, human error is in majority of the cases present as a contributing factor with serious consequences, mainly caused by high workloads. Therefore, methods to quantify the OOW's workload become an important research topic for navigation safety. Among the available maritime research studies conducted in the ship simulator, the indirect method of collecting biometric data, typically using a heart rate (HR) sensor and an eye-tracking device correlated with an individual task load index (TLX) questionnaire, predominates, *Di Nocera et al. (2015)*.

Theoretically, the change in heart rate indirectly indicates the state of cognitive load and thus the ability of the decision-making process in person's working memory to successfully avoid the potentially dangerous situation. During the simulation, the high workload of the participants is induced by challenging navigation conditions or various disturbing factors, which may lead to human error behaviour (HEA) and eventually, in the worst case, collision. The scenario was conducted in the most advanced nautical full-mission simulator to avoid real consequences, although the experiment represents only partial and limited real situations. Nevertheless, the recorded data show with statistical significance that experienced participants typically perform given tasks with a lower HR ratio, which is well known from psychology and consistent with the way information is processed in working memory, *Haberlandt (1997)*.

2. Methodology of the biometrical measurement

The trigger for the investigation of biometrics-based training in the simulator was the EMSA annual report, which identified human error as a typical cause of incidents. The question arose: is it possible to predict potential human error through biometric measurements during training? In the available literature, respected authors face several challenges due to noise in biometrically collected data caused by invasive methods and interfering sensors, *Miklody et al. (2017), Main et al. (2017)*. One of the antecedents of workload in our experiment was heart rate, and therefore we investigated the possibilities of recording participants' heart rate during the challenge using the most non-invasive method possible. We involved enthusiastically also the eye-tracking method, but soon faced the problem that participants with prescription glasses could not wear both glasses at the same time. The ultra-wideband pulse radar breath sensor for non-contact respiration measurement is a very promising method, *Košir and Kozjek (2018)*, but limited in use on the command bridge because of the movement of the OOWs from one side of the bridge to the other. The third experiment was a non-invasive biometric multi-sensor on a wristband. The device, which is the size of an average modern smartwatch, Fig.1, is relatively unobtrusive to participants and able also to monitor electro-dermal activity (EDA) and blood volume pulse (BVP). During the training, the heart rate was assumed to increase according to the difficulty of the simulation, indicating the high workload condition of the participants during the specific time of the collision avoidance manoeuvre simulation, *Žagar et al. (2020)*. In the next section, the method for non-invasive biometric measurement is described.

2.1 Experimental design

Five experienced captains with an average age of 48 years and an average length of service of 20.5 years volunteered to participate in the case study to measure HR during maritime training. The experimental design consists of two navigation phases, the control phase (easy) and the experimental phase (hard). The primary biometric sensor is the Empatica E4 multi-sensor wristband, Fig.1, with EDA, BVP, accelerometer and temperature sensor. The focus of the ad hoc questionnaire (pre-experiment) was on participants' prior experience and abilities, individual personality, and response to the simulator's ergonomics and environmental parameters, *Sumpor (2019)*. The aforementioned data were collected using the TLX questionnaire with the Linkert scale.

Fig.1: Empatica E4 wristband bio-metrical sensor, www.empatica.com

Fig.2: Full mission simulator training: Experienced participant wearing wrist-band biometrical sensor during strong wind approach to the container terminal in Port of Koper.

The Wärtsilä's TechSim5000 simulator was used for the experimental environment, combining a full-mission navigation bridge with four video projectors providing a 170° viewing angle, Fig.2. The design and ergonomics are comparable to a modern merchant ship bridge and ensure a high degree of realism. In order to provide all participants with the same environmental parameters, temperature sensor, humidity sensor, sound sensor and lighting conditions were monitored. During the simulation, only one participant was allowed to be on the bridge at a time to avoid sharing the cognitive load, which typically occurs in experiments with multiple participants and causes noise in the recorded data, *Liu et al. (2017)*. The experimental tasks were designed according to traffic analyses and accident predictions in traffic separation areas North Adriatic, *Vidmar and Perkovič (2018)*. Each simulation consists of a control and an experimental phase. The task is collision free navigation considering COLREG in the traffic separation zone where several ships were heading towards the ports of Monfalcone, Koper or Trieste. Each simulation additionally consists of the disturbance factor - unexpected sound of the fire alarm. The aim is to determine the correlation of the specific alarm with the heart rate level, which is explained in detail in section 3.

3. Results

The efficiency of cognitive processes in human working memory during training depends on the number of tasks set and correlates with participants' prior experience, *Haberlandt (1997)*. During navigation training in a simulator, the difficulty of the task depends on the traffic density in the separation zone. Together with the disturbing factor, which causes a typical biometric response and thus a prolonged reaction time due to the saturation of the cognitive part of the participant's working memory. During simulator training, saturation of working memory impairs the learning process and situational awareness, which may eventually lead to a potentially dangerous situation. Preliminary analysis and visualisation of biometric data will be performed by comparing participants' experimental and control phases.

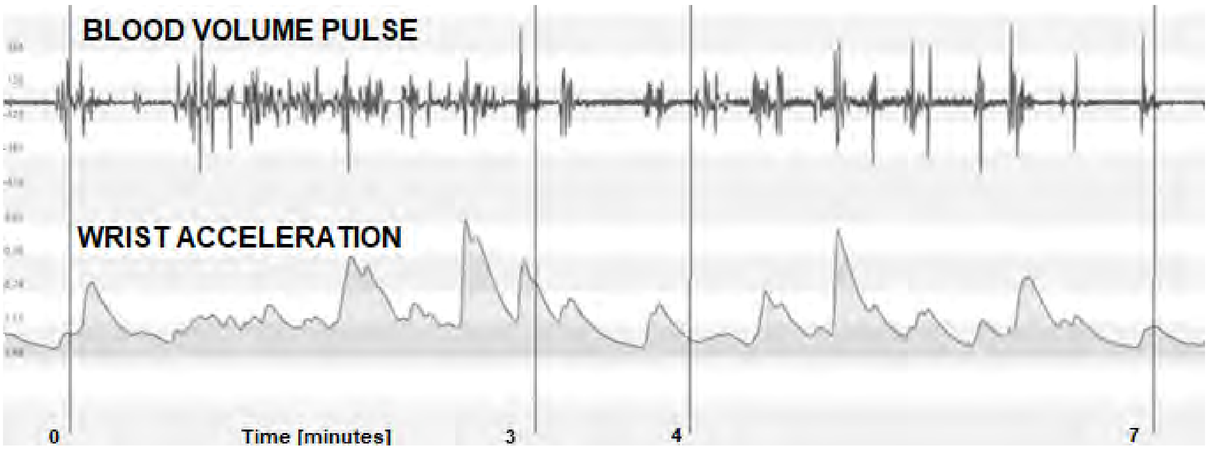

Fig.3: Biometric parameters of the 7 minutes' disturbance factor interval: Trend of the Blood-Volume pulse and the wrist accelerometer. T = 0 min – beginning of the primary disturbance factor, T = 3 min – end of the primary disturbance factor, T = 4 min – beginning of the secondary disturbance factor, T = 7 min – end of the secondary disturbance factor.

BVP indicates that the more the blood vessels dilate (vasodilation), the greater the signal amplitude, indirectly indicating a higher cognitive process during simulator training. In the cognitively demanding experimental phase, HR was on average 4% higher than in the control phase. The highest BVP values were recorded (as expected) during the disturbance factor occurring interval between T1 and T2, Fig.3. Comparing the data from the control phase, it can be seen that HR was on average 14% higher than during the disturbance factor phase. A typical biometric response during disturbance (sound of the fire alarm) is shown in Fig.3, where BVP and wrist acceleration are plotted during two alarm intervals. At the onset of the primary alarm at T = 0 min (and the secondary at T = 4 min), experienced participants typically sought the position of the mute button. As they recognize the severity of the alarm, BVP increases until T = 3min (and secondarily T = 7min) when the fire simulation is cleared and the alarm disappears. Further insights into the results are presented in the next section.

4. Discussion

During the supervised training process, the biometric measurement results confirmed the working hypotheses known from the existing literature that the average HR rate increases significantly during the cognitively demanding phase of the experiment, Fig.4. The sample of participants is small (N=5) due to the current health situation, therefore conclusions are limited. Nevertheless, the novelty of the non-invasive measurement design confirms the potential of biometrically assisted digital training. The trend of the collected data from the proposed experimental design shows the individual parameters and personalities of the participants. From the literature review, we hypothesize that the biometric response is related to the participant's personality, openness, conscientiousness, extraversion, agreeableness and neuroticism. However, individual analysis of the biometric records shows that participants differ in the extent of response. It appears that the differences correspond to the participant's individual level of reality experience, including the post-traumatic stress response that occurred when the participant was confronted with the situation, a dangerous reality experience. This fact explains the HR overlap of DF-P1 and DF-P5 in Fig.4. Post-processing of the questionnaires and interviews revealed that the participants experienced post-traumatic response, experienced the real fire on board in the past.

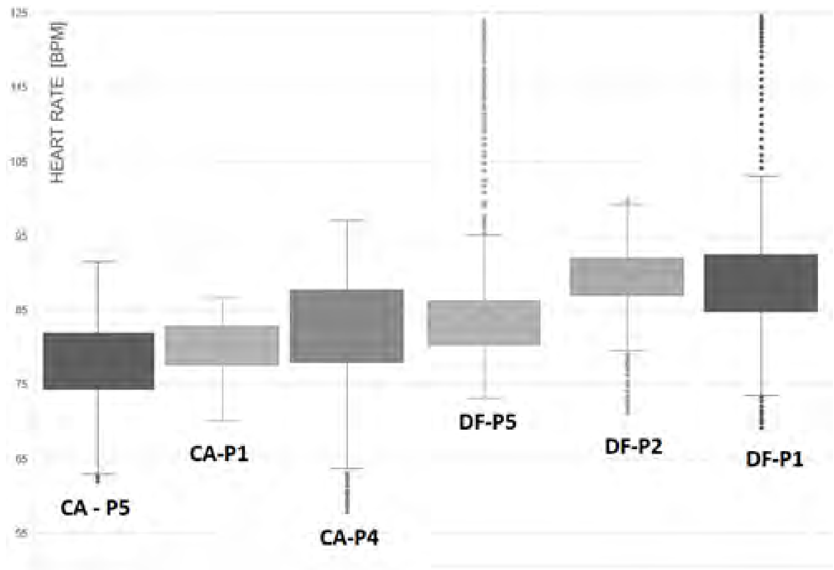

Fig.4: HR parameters during 20 minutes simulated navigational task. CA – collision avoidance task, DF – Disturbing factor task, P – participant

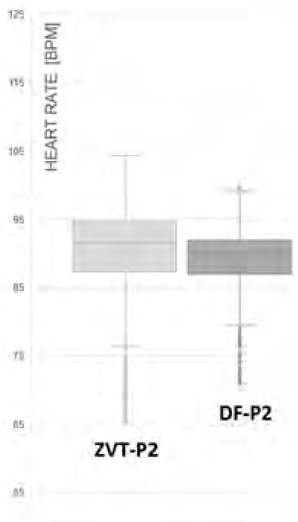

Fig.5: HR parameters during 20 minutes simulated navigational task: ZVT – zero visibility task, DF – Disturbing factor task, P – participant

The interesting observation in supervised training correlates with recent findings about human cognitive processes in working memory when we look through the prism of bridge ergonomics and environmental design. In the zero-visibility task, participants faced dense fog during simulated navigation, with navigation safety relying solely on bridge instruments. The processed data show an even higher HR rate than in the disturbing factor task, Fig.5, indicating the high cognitive load. This finding supports the assumptions that more digital devices on board do not necessarily mean higher safety, *Stapel et al. (2019)*.

5. Conclusions and future visions

Despite the fact that the conclusions of this case study are limited due to the small sample of participants and the current health situation, the result of the proposed model gives an insight into the cognitive processes of the participants during the digital training in the full-mission simulator. It has been shown that the wrist sensor does not interfere, which is promising for biometric data collection. The induced disturbing factor during supervised training in the simulator significantly affects the HR rate, suggesting that the cognitive process in working memory is saturated during the specific task, possibly leading to erroneous actions by humans. Interestingly, we observed that the zero-visibility task disrupted participants' HR rate even more than the fire alarm sound, suggesting that a higher number of instruments on the ship's bridge does not necessarily mean safer navigation. We also expect to better understand the influence of the participant's personality on the decision-making task during digital training. The next step is to develop the machine learning algorithm for real-time data processing, but the real achievement would be an attention monitoring algorithm, *Burnik et al. (2017).*

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School's in!

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Abstract

In courses of ship design and engineering the particulars of the profession are well-taught. However, driven by software and computer advancement, in the industry over the past decades new tools have emerged, such as optimization, geometric modelling, CFD, big data and machine learning. These tools have been considered too complex for an undergraduate program. Yet, some knowledge of this trade is essential on every professional level, and our proposition is that if the material is offered in a first-principle fashion, in combination with practical exercises and oral discussion, the heart of the matter can very well be educated to an undergraduate. Recently, a 30 EC minor was given in this fashion.

1. The tale of two misunderstandings

For the COMPIT audience we don't have to argue that the ICT revolution of the past decades has brought our profession much. Also in the society in general, the awareness and expectations in this respect are high, fed by the maturing of the global connectivity, and the expectations of Artificial Intelligence (AI). Expectations may even rise to unrealistic levels, an example being the "misconception regarding the electronic availability". This is the idea that if data is available in digital form – somewhere, somehow – then this is effortlessly consumable and usable in each and every computer program. A striking example of this misconception was shown when a client of one of the authors (a manufacturer of loading and stability software, www.sarc.nl) asked whether it would be possible to extend a loading program of another brand with scans of their ship-specific IMDG manual.

A second misconception is observed in *Koelman (2019)*, where the urgency of deeper education in advanced technologies is motivated by "Personally, I believe that there is a bit of an emergency; the older generation has the idea that young people are so skilled with computers because they grew up with them and are surrounded by them – the digital natives – but that knowledge is usually superficial. It is therefore necessary to offer training in digital engineering skills to those who are interested".

The first misunderstanding relies on the second, so to combat both, increasing the level of knowledge is sufficient. To this end, we recently rolled out a dedicated minor course. This is presented in this paper, not only with the objective to inform the Compit community, but also to identify opportunities for collaboration.

2. Place and content of the minor AETS

"Maritiem Instituut Willem Barentsz" is the maritime institute of NHL Stenden University of Applied Sciences, with four-year BSc courses in Ship Design, Master Mariner and Ocean Technology, as well as an MSc course in Marine Shipping Innovation, www.nhlstenden.com/en/miwb. The first semester of the fourth BSc year is allocated for a 30 EC (at 28 hours/EC, corresponding to 840 hours) minor. The advantages of using a minor for our ambition are a) its relatively long time span, b) its position later in the course, which makes that students have already a bit of a substantial body of skills and knowledge and c) the fact that minors are elective, so that only students with genuine interest will attend.

The minor was baptized "Advanced Engineering Tools for ShipX", where X is a placeholder for design, operation or management. Its content consists of seven courses on:

- Workable knowledge with Python, 4 EC.
- Numerical methods in engineering, 3 EC, in particular maritime applications of numerical differential equations and statistics.
- Linear programming and non-linear optimization, 3 EC.
- Data and shape modelling, 5 EC, in particular conventional regression (linear and polynomial) and ship shape modelling. As well as their interrelations.
- Hands-on experiments with computations on stationary fluid flow (with a commercial CFD package), 4 EC.
- Classification of data, and a too brief introduction into AI. Including an outlook into the normative aspects of these technologies, 5 EC.
- A research assignment of 6 EC, where the students are invited to apply the learned techniques on a maritime subject of their own liking.

The courses are taught with introductory lectures, references to relevant literature, and assignments, many assignments, which are performed in alternating groups of two or three persons. Deliverables consist of reports, working computer programs, presentations and an occasional podcast.

The governing learning strategy is where possible to minimize the use of too complicated mathematics, and to rely on elementary physical or mathematical mechanisms instead. For example, a planar moment of inertia (I) is usually educated using Steiner's theorem, which in its turn is derived by analytical integration. Our proposition is that by this detour of integration + theorem the insight into the heart of the matter is obfuscated. While the essence of I is simply the summation of every tiny piece of area multiplied by the square of its distance from centroid. Cumbersome to compute in this fashion for a human, but for a computer only a trifle. Such a ‘first principle’ approach illuminates the essence, while the use of previously derived “theorems” only obscures it.

In this sense there is an analogy with “object lessons” (Dutch “aanschouwelijk onderwijs”, German “Anschauungsunterricht”), a concept attributed to Comenius (1592-1670). Its original implementation was that in addition to language (Latin, in those days), objects or visuals may serve better for students to receive or discover ideas. The correspondence is that also in our view the language of higher mathematics is not always the best instrument to transfer knowledge. For our audience.

3. Highlights of some of the courses

Ideally, we would like to recite the minor in its entirety, but lack of space and your patience won't allow it. So, we will elucidate a few noteworthy things.

3.1 Programming, numerical methods and optimization

The aim of the Python course was to provide the students with a practically useful tool. In this respect Python is superb; it is generic, elegant, supported by a vast amount of resources (forums, books, a nice learning app; Sololearn) and a plethora of libraries with all kinds of tools and functions for mathematics, numerical analysis, text processing, file management, data analytics, AI etcetera. A funny aspect of Python is its dynamic typing, which initially hides the importance of typing. Attractive for beginners, although in somewhat more mature applications type incompatibilities and related confusions still will pop up. An illustrative example popped up with an exercise with Holtrop’s method for resistance prediction. Due to an input error one of the parameters was way out of range, and inserted into the Holtrop equations it led to a negative number being raised to a real power. Upon the resulting Python error message, the student found an alternative mathematical library, which did not tag the equation as erroneous, and gave a nice number as result. Actually two numbers, because the solution of this equation lies in the complex plane, so the ship’s resistance consisted of two components, one real and one imaginary. Would Python not be that forgiving with types, quite some confusion would have been avoided. Anyway, this is just anecdotic and a minor detail, Python is the best language for our goals.

It may be obvious that just four EC is insufficient to educate seasoned Python programmers. But that has never been the goal of this minor. Programming skills up to the level of numerical operations, functions, file I/O, simple graphs and the usage of external libraries are sufficient, for now.

Another illustration of our aim to leave out maths wherever possible is the exercise of the heave motion of a vertical cylinder. The standard textbook solution requires some mathematical skills, resulting in the well-known logarithmic decrement. However, with Newton's second law and numerical integration in small time steps the solution is also found. And not with less understanding, because that is not in the mathematical analysis, it is in internalizing F=m·a, and its power in practice. After this exercise, the student is gently reminded that the analytical solution is only valid for linear cases, while the numerical one is universal.

Another example is the way non-linear optimizations are taught. We are not talking about gradient and Hessian matrices (well, we show one slide with partial derivatives for a few seconds to illustrate there is more background than we elaborate), but try to make the algorithms palpable with the analogy of looking for the top of a mountain while standing on its flank in the fog. To paint a picture of the form of student assignments, two examples of optimization problems are presented in the appendix.

3.2 Data and shape modelling, and CFD

The data modelling part contains exercises with linear least squares regression, applied on 2D and 3D linear as well as 2D polynomial functions. A non-programming exercise was the modification of a vessel's bulb shape, with a dedicated hull shape modelling program, Fig.1. This ship was the same as subsequently used for CFD, and as an intermediate step a physical model was prepared for 3D printing, Fig 2.

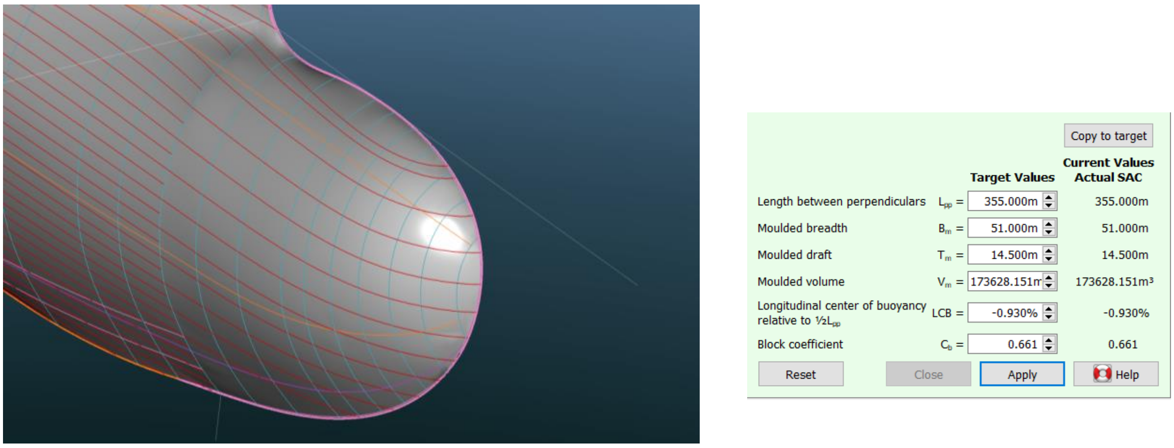

Fig.1: Bulb shape modification exercise

Fig.2: A subgroup of students proudly showing their 3D print

This CFD course gave us a bit more than three weeks to teach the very first principles of stationary flow around the hull, and the related resistance. To students with basic knowledge of fluid flow around the hull, resistance components, shallow water effects and empirical estimation methods for resistance. But without prior exposure to potential flow or Navier-Stokes. In order to teach the students a practical application, a full-blown commercial CFD program was chosen for these exercises. In this case STAR-CCM+, by Siemens. One of the reasons for this choice was the associated extensive helpdesk support as kindly offered by Femto, www.femto.eu.

With the assistance of an external tutor, www.sastech.nl, an achievable goal was formulated; that at the end of the course the student is capable, in her or his role as ship designer, to order a CFD calculation with an external specialist, and to be able to understand the reported results and conclusions in a responsible manner. Thanks to hard work of the students, in this short time span they independently managed to produce reliable results, Fig.3.

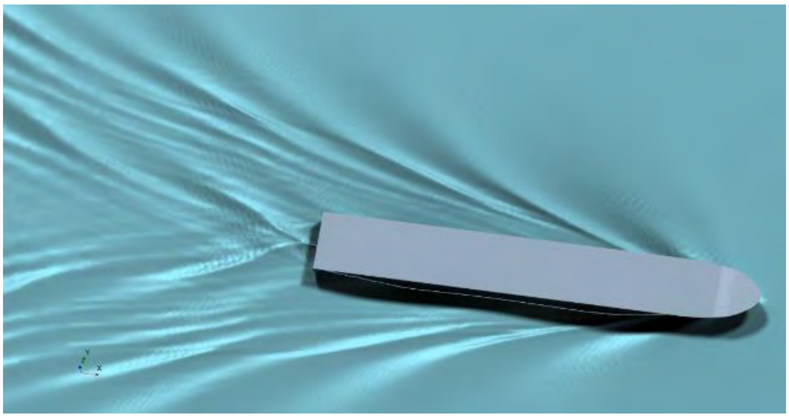

Fig.3: An example of a student's result after two weeks of CFD training and exercises.

3.3 Data science and the research assignment

The data science course changed the mood a bit. Until now the emphasis was on algorithms and programming, but here a number of speakers from the industry were invited to present their vision, developments and achievements. With the idea to build a bridge between theory and practice. Yet, this course also contains a programming assignment, or actually a match, where a (moderately polluted) database with all kinds of general particulars of 13,000 ships was supplied. The task was to learn an algorithm to derive the ship type from its particulars. The winner is the group with the highest score on a separate test set.

A single EC from the data science course has been dedicated to normative aspects of algorithms and AI. Here some papers and podcasts have been supplied, with the student's task to reflect and report, also in a Podcast, on two of the supplied propositions, from which examples are:

- There is a positive relationship between the amount of data available and the quality of the product designed with it.
- One day an autonomous sailing boat in the Rainbow class (https://regenboogclub.nl/de-regenboog/) will win a major sailing contest.
- Offensive autonomous naval vessels should be banned.
- Only when autonomous (sea, road or air) vehicle control is guaranteed to be safe it should be allowed in public.

For the research assignment each student chose an individual subject:

- Optimization of frame spacing for minimum weight.
- Machine learning system for determining causes of Engine Room alarms.

- Determining deck construction using a variable frame spacing.
- Application of Neural Networks in Ships' Autopilot settings.
- Track optimization in an Yngling sailing race.
- Optimization of ship routes in extreme waves.
- Optimization of ferry service across Amsterdam IJ.
- Application of water bags to improve stability during lifting operations.
- Analysis of trends in larger container ships.

This course was closed with a short paper and a mini-symposium.

4. Results, appreciation and the lessons learned

Looking back, we can conclude that quite some exercises have been made with reasonable success, for example:

- Heave motion in time domain.
- Cross-flooding time in case of damage (first-principle).
- Double pendulum (note www.myphysicslab.com/pendulum/double-pendulum-en.html contains a nice illustration of the phenomenon).
- Weather routing (a specimen of nonlinear optimization).
- Regression and correlation.
- Spline curves and surfaces.
- Hull shape design.
- Machine learning: ship type classification.
- The research assignment results in four of the mini papers to be published in a Dutch professional journal.

Subjects where students unintendedly spend a bit too much of their time looking for clues have been:

- In optimization, the difference between optimization goal and boundary conditions.
- A bit of installation hassle with CFD. Fortunately, with the tremendous support of the supplier and the NHL Stenden staff this was quickly resolved.
- Occasionally with the wave spectrum (which, by the way, has been taught in other courses in lecture form before).
- With the manoeuvring exercise. In hindsight the problem could be traced back to incomplete formulation of the exercise (where a rocket was intended to be at rest in vacuum in space, which was not clearly mentioned, so the students envisioned the rocket to be launched from earth under the influence of gravity, a somewhat more complicated situation).

We started the CFD course fully concentrating on the installation and operation of the CFD software package, based on the idea that basic concepts of flow and resistance have already been addressed in courses on hydrodynamics. That was a step too far, to which should be added that the Master Mariner students did not have this background anyway. So, next year's CFD course will start with some introduction on flow phenomena, consisting of e.g.:

- A lecture, presenting these subjects in a visual way ("object lessons"). Supported by some of the tons of available Youtube videos.
- An exercise with a fluid flow training tool. To this aim we will actively experiment with the program Lily Pad, as presented in *Weymouth (2015)*.
- Material from other sources or institutes. E.g. *Vaidya (2020)* provides a nice literature overview (although most of it does not relate to moving objects at the interface between two mediums).
- A Python programming assignment with 2D potential flow with a few sources and sinks, leading to (variants of) the Rankine oval. Such a task a) forms the glue between the preceding

programming exercises and CFD, while b) this is CFD in its most elementary form and thus hopefully provides some insight into its principles.

Finally, we do not want to leave unmentioned a few remarkable quotes from the student survey:

- Hold on and be patient, it's all going to be fine.
- Tip for students next year: immerse yourself in the assignments and take some time to play around with them a bit. Eventually you will come to a solution.
- The guidance and tips in the past year have been very useful, it really is a top minor. The assignments last year were sometimes unclear, but I expect that that will be adjusted. I really liked the idea of working in as many different teams as possible and I would recommend it for next year.

5. Conclusion and appeal for additional exercises

The minor AETS was recently given for the first time and was quite successful. Next year the intake restriction will be removed, and the minor will also be open to students from outside NHL Stenden. We are considering offering it as a post graduate course as well.

Finally, we would like to make an appeal to the reader. The COMPIT audience is known for its significant share of professors and lecturers, some of whom might have been involved with a similar endeavour. If you happen to have useful material – exercises, data sets, research topics, video clips etcetera – and are willing to share it, please contact the authors.

Acknowledgement

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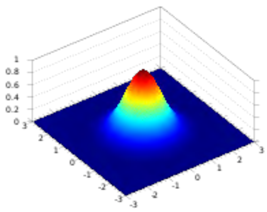
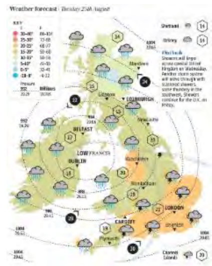
Appendix with two examples of optimization assignments

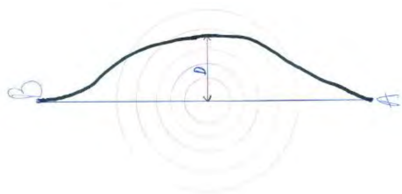
Weather routing



A ship is sailing from A to B, a distance of 3000 nm. Right in between, summer storm Francis is developing, with wind gusts to 70 mph. Wind and waves in this storm lead to speed reduction, which is modelled by a symmetrical two-dimensional Gaussian function, see https://en.wikipedia.org/wiki/Gaussian_function#Two-dimensional_Gaussian_function, as depicted at the left, with standard deviation $\sigma_x = \sigma_y = 1000$nm. The ship has a design speed of 16 knots, while the maximum speed reduction in the middle of the storm, parameter A of the Gaussian function, is 10 knots.



1. The master of the ship is inclined to smooth manoeuvering, so she chooses a cosine-like (in the interval 0 to 2π) trajectory shape, with a maximum distance D from the undisturbed trajectory. According to the sketch right. Please determine D which leads to the quickest passage through the storm.
2. This computational model is rather simplified. Please reconsider the whole aspect of ship routing, and conceptualize a more realistic model.



Fleet optimization

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Optimal vessel speed and fleet size for industrial shipping services under the emission control area regulation

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Please scan supplied paper *Optimal vessel speed and fleet size.pdf*, which contains a useful method to optimize a fleet for ECA areas. As side product this paper contains a concise formula to determine the optimal size and speed of a fleet of (equal) ships, see eqs. 1a, 1b and 1c. Regrettably, in these equations the effect of higher speed on engine wear and lubrication oil consumption is not included. In order to compensate for this effect, the last factor of eq. 1a (+ γN) is multiplied by an 'engineering coefficient' of $(0.9 + 0.1 \text{ x } v^2 / v^2_{design})$.

If this equation is applied on a fleet of ships with these consumption rates

Fuel consumption ton/day	33
Fuel consumption ton/hour	1.375
Design speed knots	18.2

and these financial data (with notations according to table 1 of the paper):

K	1000
S	6000
Ic	2
L	1200
gamma	1500000
eta2	600
D	200000
Tp	48

then determine the combination of v (sailing speed) and N (number of ships in the fleet) which minimizes AFC (Annual Fleet Costs).

Assessing Semi-Autonomous Waterborne Platooning Success Factors in Urban Areas

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Abstract

A waterborne platooning concept, i.e. a Vessel Train (VT) it is composed of a fully manned lead vessel that takes over navigational responsibility for the followers. Joining a VT helps improve the competitiveness of smaller vessels and increase their use, as it allows a vessel to sail continuously with a small crew. This paper identifies the challenges created when penetrating urban areas and models the viability of the VT. The influence factors of the implementation hinge on the maximum opening times and on the simultaneous opening of adjacent bridges. The results provide guidelines for a successful integration of the semi-autonomous platooning system in urban areas.

1. Introduction

The rising ownership and use of private and commercial road vehicles cause a worsening of the congestion situations across Europe, *ACEA (2019)*. In the Netherlands, the average driver spends 37 h per year in traffic jams, *Jorritsma et al. (2020)*. One way to reduce these road traffic delays is to move cargo from the road to the waterways. In countries that have extensive waterway networks such as Belgium and the Netherlands, this may lead to more congestions due to bridge opening in urban areas or even leading into metropolitan areas. Using waterborne platooning can help cluster the vessel passages and reduce the number of bridge openings. This paper studies the implications and implementation requirements of a waterborne platoon in urban areas.

The NOVIMAR project (https://novimar.eu/concept/) is developing a waterborne platooning concept referred to as the Vessel Train (VT), that aims to improve the competitiveness and service level of waterborne transport. Its intention is to bring waterborne transport into urban areas, through enhanced use of smaller vessels. The Vessel Train concept consists of a fully manned lead vessel (LV) that is digitally linked to a number of follower vessels (FV), for which it assumes navigational control. Moving the navigational tasks to the LV allows the FVs to either reduce the size of their crew and the associated crew cost or improve the productivity of the vessels. The productivity gain is achieved since inland vessels can choose to only operate 14 or 18 hours per day with a smaller crew (i.e. two or three crew members). If the navigation-related tasks are taken over by the LV, the FV can keep sailing while the crew is resting, thus allowing 24-hour operations with a crew for 14 or 18 hours. The FV crew left on board is still able to navigate the vessel on its own outside of the VT. Hence, the operating flexibility of the followers is ensured.

1.1. Prior research

1.1.1. Waterborne platooning

Most literature studying the application of the waterborne platooning concept for inland navigation originates from the NOVIMAR project. It researches, among other aspects, the economic viability of the Vessel Train. Relevant publications from this project include *Meersman et al. (2020)* and *Colling and Hekkenberg (2019,2020)*. *Meersman et al. (2020)* present an extensive overview of direct and societal cost for different viable scenarios in which the vessels could choose to join the VT that serves existing cargo flows. *Colling et al. (2020)* identify a minimum VT length and a required number of participants for a VT liner service with different inland vessel types. This paper builds on the latter research by identifying the additional requirements that urban areas create to allow a successful implementation of the Vessel Train concept.

1.1.2. Obstacle passage

Numerous studies exist on the topic of bridge passage. In the early 1990s *Larsen (1993)* suggested bridge designs to avoid collisions on densely used waterways. More recently, the topic has gained importance with regards to obstacle avoidance of autonomous navigation systems. *Ramón et al.'s (2009)* research the use of navigational systems such as laser detection and ranging (lidar) to help avoid collisions with bridges. Others like *Heßelbarth et al. (2020)* elaborate on the difficulties of bridge passage that cause a temporal block of communication signals.

Procedural optimisation of "obstacle" passage has mainly been dealing with lock passage, as locks are one of the main capacity limiting factors for waterways, *Backalic and Bukurov (2011), Uchacz (2013)*. Research on the procedural optimisation of bridge passages has been limited to the Dutch province of Noord-Holland setting up the *Blauwe Golf (2020)*. The *Blauwe Golf* (Blue wave) uses bridge management systems that give bridge operators an opening advise using input from emergency services. This optimises the traffic flow near bridges to improve the conditions for the road and waterborne users by reducing the number of bridge openings. The research presented in this paper adds to the developments of the *Blauwe Golf* by identifying how the VT - bridge interaction can help cluster vessel passages.

1.2. Research Focus

The research questions addressed in this paper are:

1. What are the factors that influence the VT- bridge interaction when penetrating urban areas?
2. Under what conditions is the VT penetration into urban areas viable?
3. What market share does the VT need to achieve to provide congestion benefits to the road traffic?

This paper identifies the most influential factors regarding VT-bridge operation interactions and calculates the effects they have on the length of the VT, i.e. the number of FVs possible, in urban areas. These factors are related to the infrastructure of a bridge, the impact on land traffic and bridge operation regulations. In order to assess these factors, a model was developed that assesses both the requirements for the road and the waterborne traffic. This model is applied to a case study in the province Noord-Holland leading along urban area into the metropolitan area and ends in the port of Amsterdam.

2. Vessel Train potential and challenges in urban areas

The historical data gathered by the province of Noord-Holland in 2018-19 shows that on average, 97 % of bridge openings happen for a single vessel passage, *Provincie Noord-Holland (2020)*. Bridges are usually not open for longer than 10 minutes, where 3.5 minutes are needed to actually open and close the bridge, *Backers (2020)*. Given the fact that some bridges open up to 6000 times per year, one can deduce that clustering vessels in fewer bridge passages has the potential to save days' worth of road traffic waiting times along an entire route that leads into urban areas.

2.1. Benefits

The improvement of competitiveness achieved with the VT by the reduction of crew cost or enhancing the productivity can influence a modal shift towards waterborne cargo transported. The improvement of the competitiveness is targeted in particular at the smaller vessels, that can take less advantage of the economies of scale. This is one of the reasons why smaller vessels are continuously diminishing in numbers with no new built vessels joining the fleet, *van Hassel (2011)*. Modal shift from road to water has a positive effect on the environmental impact of transport as inland vessels still have a smaller environmental footprint than road transport, emitting 17% less CO2 and 34% less NOx, *Otten et al. (2016)*. Additionally, the VT implementation leads to clustering of vessels, thereby requiring fewer bridge openings which can create a societal benefit through the reduction of road user waiting times.

2.2. Challenges

There are also factors that make the clustered passage of vessels in a VT challenging. These factors concern traffic density, regulations and infrastructure. Each of which are discussed below.

2.2.1. Traffic density

The traffic density on a waterway is a crucial factor when considering the deployment of a VT. The implementation area needs to ensure sufficiently large cargo flows to have enough vessels joining the VT. An additional influential factor that can pose a challenge to the VT navigation is the presence of a large number of recreational or non-cargo vessels that complicate the autonomous navigation of the FVs.

2.2.2. Regulations

The urban penetration of the VT may be hindered by regulatory restrictions regarding the maximum number of simultaneous adjacent bridge openings. Interviews with bridge operators and Province of Noord-Holland representative concluded that, bridge located in the vicinity of emergency services may at a moment's notice need to close to allow emergency services to reach their destination within a reasonable timeframe. For the same reason, the province aims to, dependent the traffic conditions, have no more than two adjacent bridges open simultaneously. Additionally, some bridges do not accommodate openings during rush hours, in order to minimise the traffic jams created, *Backers (2020)*. Furthermore, some bridges in urban areas do not operate at night (between 23:00h-05:00h) unless special permission is granted. This emphasises the need for careful planning. While this is not a VT specific problem, it can prevent the VT users from reaping the VT's greatest benefit of an improvement in productivity by operating continuously with a smaller crew. The bridge operating hours may change if the demand requires it, yet the restrictions of adjacent bridge openings and rush hour openings are likely to stay in place even with a greater use of the waterways.

2.2.3. Infrastructural limitations

One infrastructural factor is the size of the waterway, which influences the maximum size of vessels. Smaller vessels of CEMT class I-III are more likely to reach into urban areas than larger vessels, since waterways leading into urban areas are typically small. Another infrastructural aspect is the distance between bridges. As the number of simultaneous adjacent bridge opening is limited to two, the distance between these bridges plays a decisive role in determining the maximum possible VT length and safety distances between vessels that are required to sail on a given route.

Finally, the number of bridges along the route influences the VT operations. Every bridge passage requires the VT to reduce its sailing speed. This lower speed needs to be kept until every vessel has passed the open bridge, as the speed limits on the urban waterways do not allow FVs to catch up with a LV, if they were to speed up after passing the bridge themselves. Thereby, every bridge passage and vessel in the train will add additional time to the trip compared to the operations of a conventional vessel would experience. In order to quantify the effects of these influence factors on the viability of urban penetration with the VT, the factors are incorporated in a model and a case study that applies the model.

3. Methodology

To identify the circumstances needed for a viable penetration of the VT, a model has been developed that compared the road based to the waterborne traffic conditions. A viable urban access is defined by ensuring: 1) economically viable VT length 2) that regional regulatory limitations are met and 3) that at least equivalent congestion situation to the current situation is achieved. Attaining additional congestion benefits is desirable to gain political support for the implementation of the VT concept.

The calculations presented in this methodology are targeted to quantify three aspects of the VT-bridge interaction:

1. The maximum bridge opening time from a road-based perspective
2. The maximum required bridge openings from a waterborne perspective
3. The reduction in road-based waiting time that clustering of vessels can achieve

The maximum bridge opening time determines whether the road conditions allow for economically viable VT operations to take place, while the number of required simultaneously bridge openings, defines if the waterborne infrastructure allows viable operations. The reduction in waiting time due to the clustering of vessels is needed to calculate the societal congestion cost-benefit. Savings in congestion cost can help sway the municipalities to loosen regulatory restrictions, which can help the implementation of the VT. Looking ahead to a longer term, the congestion cost savings can also potentially improve the viability of the overall concept if the political decision were to be made to internalise external cost.

Fig.1 provides a visual representation of the type of data (in the cylinders) used to determine the model results (in the rectangles). Two viability checks have been created (in the hexagons) to ensure the road and waterborne infrastructure conditions allow for economically viable operations of the VT. The first viability check compares the performance of the road condition with the minimum opening required for the VTs to pass. The second, checks whether the spacing between the bridges allows for the VT to pass without opening more than two bridges simultaneously. Lastly, a large congestion cost benefits can help argue the adaptation of regulatory limitations for the VT operations or potentially reduce the required number of FVs through the internalisation of external cost. This is represented by the dotted lines in Fig.1.

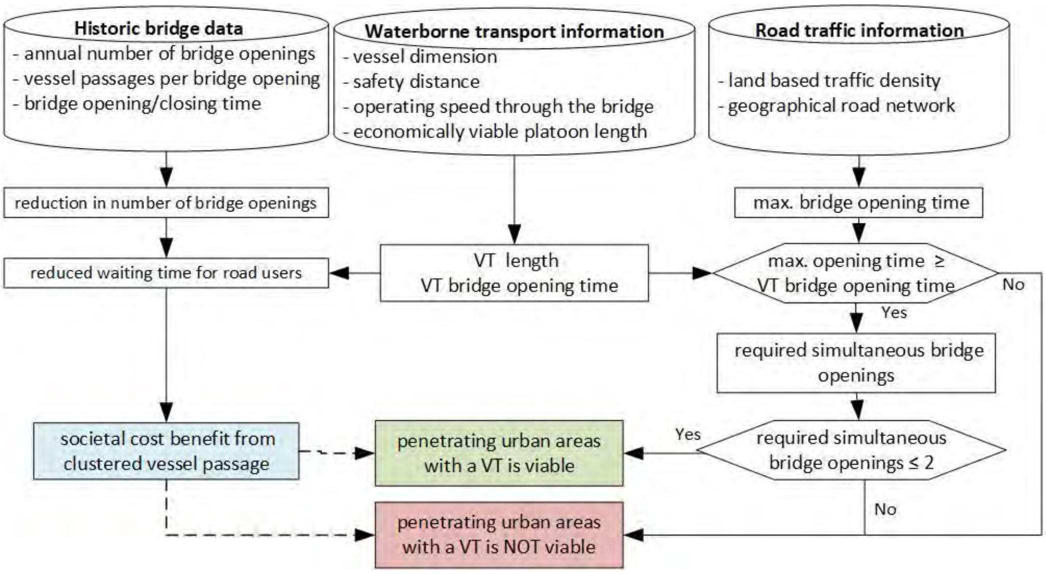

Fig.1: Methodology structure

3.1. Maximum bridge opening time

The maximum bridge opening times are calculated based on the assumption that the bridge opening is only allowed to cause standstill traffic jams in the immediate roads leading to/away from the bridge. This sets the maximum allowed traffic jam length equal to the distance to the closest road intersection. The maximum opening time of a bridge is hence dependent on the formation and dissipation of the traffic jams. The length of a traffic jam is calculated with *Jeihani's (2015)* traffic jam theorem, in which the opening of a bridge can be compared to the modelling of a traffic incident or a red traffic light. The theorem uses traffic intensity in vehicles per hour and traffic density in vehicles per km information to determine the amount of time and length it takes for the congestion to dissipate. Eq.(1) calculates the queue build-up rate, which is the number of km with which the traffic jam grows per hour (km/h).

$$u_1 = \frac{q_2 - q_1}{k_2 - k_1} = \frac{0 - q_1}{k_j - k_1} \tag{1}$$

u_1:	Queue build-up rate (km/h)	k_1:	Pre-incident density (vehicles/km)
k_2:	Incident density (vehicles/km)	k_j:	Jam (incident) density (vehicles/km)
q_1:	Pre-incident flow rate (vehicles/h)	q_2:	Incident flow rate (vehicles/h)

For stationary traffic, the number of vehicles per hour of the outbound traffic is equal to 0. When the bridge is down, all the vehicles can drive again. The queue dissipation rate, once the traffic is rolling again can be determined using Eq.(2). Once the bridge closes there is no traffic in front of the first car. Therefore the capacity flow rate is equal to the maximum flow rate. This means that the traffic is in a state of 'free flow'; the maximum rate of cars can dissipate the traffic jam. This is also the reason why the incident flow rate is set to 0.

The maximum allowed jam distance up to the closest intersection is known. Hence, the queue dissipation time can be calculated. Once the dissipation time is known, Eq.(4) can be inserted into Eq.(3) to solve for the incident time, which is the maximum allowed opening time of the bridge.

$$u_2 = \frac{q_3 - q_2}{k_3 - k_2} = \frac{q_{max} - 0}{k_c - k_j} \tag{2}$$

$$t_2 = \frac{Q}{u_2 - u_1} \tag{3}$$

$$Q = t_1 u_1 \tag{4}$$

k_c:	Capacity (dissipation) density (vehicles/km)	q_3:	Capacity flow rate (= q_{max}) (vehicle/h)
q_{max}:	Maximum flow rate (vehicle/h)	Q:	Maximum allowed queue length until next crossing (km)
t_1:	Incident duration (h)		
t_2:	Queue dissipation time (h)	u_2:	Queue dissipation rate (km/h)

3.2. VT length

The VT length depends on the length of the vessels in the VT, the safety distance between the vessels and the space before/after the train, at which the bridge starts to open or close. It is expressed by Eq.(5).

$$L_{VT} = d_{aft} + d_{front} + L_{LV} + \sum_{i=1}^{n}(L_i + d_{sw}L_i) \tag{5}$$

d_{aft}:	Spacing between VT aft and bridge at closing initiation (m)	d_{front}:	Spacing in front of VT when the bridge should already be fully opened (m)
d_{sw}:	Safety distance factor between vessels	L_i:	Length of FV i
L_{LV}:	LV length (m)	n:	Number of follower vessels in VT

3.3. VT bridge opening time

The VT length determined in section 3.2. is used in equation 6 to determine the bridge opening time due to the passage of the VT.

$$t_{VT} = \frac{\frac{L_{VT}}{1000}}{v_{lim}} + t_{o\&c} \tag{6}$$

$t_{o\&c}$: Opening and closing time of the bridge (h)
t_{VT}: Opening time for the VT bridge passage (h)
v_{lim}: Limited operating speed of VT at bridge passage (km/h)

3.4. Required number of simultaneous bridge openings

The maximum required number of simultaneous bridge openings along the length of a given route is calculated by Eq.(7). This is based on identifying the space available at each section between bridges and is compared to the length of the VT in Eq,(8).

$$b_o = \max(o_x) \tag{7}$$

$$o_x = \min_{o \le b_r} \sum_{j=x}^{o} s_j \ \ge L_{VT} \text{ where } x = 1 \ldots b_r \tag{8}$$

b_o: Maximum required bridge opening along the route
o_x: Number of open bridges at a specific section x along the route
b_r: Number of bridges on the route
s: Length of the section between bridges

3.5. Reduction in the number of bridge openings

The expected reduction of bridge openings is deduced from an estimate of the required number of FVs that are needed to create economically viable operations for the VT organisers. The calculation of these values as well as an estimate for the expected market share is taken from the research presented in *Colling et al. (2021)*. The number of single-vessel bridge passages is based on the historical data and is inserted into Eq.(9).

$$s_{bo} = p_s m - \frac{p_s m}{n_{min}} \tag{9}$$

m: Market share of VT implementation (%)
p_s: Number of annual single vessel passages
n_{min}: Number of FVs in VT to make it economically viable
s_{bo}: Number of saved bridge opening per year

3.6. Reduction in waiting times for road users

While scheduling benefits may be created by having longer opening times, these benefits are not quantified within this research. For there to be a congestion benefit, the time it takes for all follower vessels to pass shall not surpass the bridge opening time for a single vessel. Eq.(11) expresses this basic conditions that needs to be met for a congestion cost-benefit to be achieved. The reduction of waiting time is the difference between the reduced number of bridge openings and the added time per bridge passage for the additional vessel times, which is taken for all bridges along the route.

$$t_{p_s} = \frac{\frac{d_{aft}+d_{front}+L_{LV}}{1000}}{v_{lim}} + t_{o\&c} \tag{10}$$

$$\frac{\frac{\sum_{i=1}^{n}(L_i+d_{sw}L_i)}{1000}}{v_{lim}} \le t_{p_s} \tag{11}$$

$$s_w = \sum_{j=x}^{b_r} \left(\frac{p_s m}{n_{min}}\left(t_{VT} - t_{p_s}\right) - s_{bo} t_{o\&c}\right)_j \tag{12}$$

t_{p_s}: Time for a single vessel passage (h)
s_w: Waiting time savings for road users (h)

3.7. Congestion cost-benefit

The number of vehicle-kilometres saved is the product of the saved waiting time, the traffic intensity and the length of each vehicle (including the safety distances between vehicles). The saved number of vehicles together with the generalised societal congestion cost values, provided for different road users, determine the total societal cost savings due to a reduction in congestion.

$$s_{con} = q_1 \, s_w \frac{L_v(1+d_r)}{1000} c_{con} \tag{13}$$

c_{con}: Cost of road congestion (€/v-km)

d_r: distance between road vehicles (% vehicle length)

s_{con}: Savings due to congestion reduction (€)

4. Case study

This section is an application case of the methodology described in section 3. Section 4.1. introduces the route of the case study, that passes through the Dutch province of Noord-Holland and ends in Amsterdam. The input data for this route is listed in section 4.2. Section 4.3. describes the case study results and concludes whether it is viable to penetrate the urban area leading into Amsterdam with the VT.

4.1. The route

The route for the case study was picked based on waterborne and road traffic density, the waterway size, bridge distances as well as the data availability from the bridge management systems of the province Noord–Holland. The route starts on the western side of the Haarlemmermeer polder Ringvaart and runs between the Kaag and the IJ, in the centre of the port of Amsterdam, Fig.2. It is the most intensively used urban waterway in the province of North-Holland and has short bridge spacing in the metropolitan area of Amsterdam. It is a segment of the inland waterway connecting the port of Rotterdam and the port of Amsterdam. Table I provides an overview of the operations along this route. Based on the dimensions of a CEMT class II vessel with an air draught of 4.7 m, *Rijkswaterstaat (2011)*, 14 of the 19 bridges that are crossed along the way have to open. As the VT is targeted for cargo vessels, only the average number of bridge openings for cargo vessels are considered and not the large number of recreational vessel passages. The average number of bridge passages is to about 97% composed of single vessel passages. Finally, the map in Fig.2 also indicates the location of emergency services that may cause immediate closer of a bridge or may limit the number of adjacent bridge openings.

Fig.2: Case Study Route, https://www.google.com/maps

Table I: Route features

Operating between	De Kaag <-> Port of Amsterdam
Route Length	25,6 km
Number of bridges	19*
Number of bridges with available data	5*
Average distance between bridges	1,3 km
Average number of openings (cargo vessels)	1660/ year*
Bridge opening times	5:00 h - 23:00 h*
Waterway size	Up to CEMT III

* Source: Provincie Noord-Holland (2020)

4.2. Input Data

Not all 19 bridges have complete data available for the waterborne side in terms of the annual number of bridge openings, not for the road-side in terms of the average vehicle length, traffic intensity, maximum traffic jam length and the average operating speed of the vehicles. The data that is available is provided in the appendix. Where the data is not available, the average of all other available data points is used instead. These averages are presented in Table II. The road traffic is modelled for average day and rush hour conditions.

The case study is applied for a varying number of FVs in the train. Dependent on the development stage of the VT technology, *Colling et al. (2021)* have identified a minimum number of FVs to create an economically viable case for CEMT class II vessels. A fully matured control system only requires one FV. In the early stages of the implementation, additional monitoring crew is needed on the LVs; hence the required number of FVs rises to three FVs, in case the originally sailing condition of the reference vessel is continuous, and up to six FVs, if the reference vessel only operated for 14 h per day. Based on this data, the vessel type chosen for this case study is also a CEMT class II.

The congestion benefits are calculated by using the metropolitan area cost for 8 of the bridges. The remaining 6 of the bridges are considered to be located in an urban environment. The market shares of the VT for these results will be varied from 1% to 100%.

Table II: Input data for case study

Input data	Value	Unit	Source
Waterborne Traffic			
Vessel Length (CEMT 2)	85.0	m	*(Rijkswaterstaat., 2011)*
Operating speed	8	km/h	*(Balduyck, 2013)*
Limited operating speed at bridges	6	km/h	
Distance before LV and after last FV	0.13	km	1 min at 8 km/h (*Backers, 2020)*
Bridge opening and closing time	0.058	h	*(Provincie Noord-Holland 2020)*
Safety factor between vessels	1.5	Ship lengths	*(Hekkenberg & Colling, 2020)*
Road Traffic			
Vehicle length (average day; rush hour)	4.6; 4.2	m	*(NDW, 2020)*
Vehicle speed (average day; rush hour)	83; 70	km/h	*(NDW, 2020)*
Intensity	746; 1253	veh/h	*(NDW, 2020)*
Max Intensity	2500	veh/h	*(Knoop & Hegyi, 2020)*
Max jam length	1200	m	*(NDW, 2020)*
Distance between road vehicles	10	%	
Congestion Benefit			
Metropolitan area, car	242.6	€ct/vkm	*(Korzhenevych et al., 2014)*
Metropolitan area, truck	460.9	€ct/vkm	*(Korzhenevych et al., 2014)*
Urban area, car	75	€ct/vkm	*(Korzhenevych et al., 2014)*
Urban area, truck	144	€ct/vkm	*(Korzhenevych et al., 2014)*

4.3. Results

4.3.1. Maximum bridge opening time

The maximum opening time for the available bridge data is presented in Fig.3. Each set of bars is representative of a bridge along the route. The blue bars present the time a bridge can be open in normal traffic conditions for an average day in 2018. The red bars show the bridge opening times for the same bridges during rush hour. The faintly coloured bars show bridges, where only indicative data was available since the data quality was insufficient. In close proximity to Amsterdam, which are the two sets of bars on the right-hand side of Fig.3, the bridge opening times are significantly shortened because the intersections are very close to one another.

The required bridge opening times for the VT of one, three and six FVs require 8.5 min, 12.7 min and

19.1 min, respectively, with a safety distance of 1.5 ship lengths between vessels. If this safety distance were to be reduced to 0.5 ship lengths, the required bridge opening time diminish to 7.6 min, 10.2 and 14 min. In either case, the feasibility check with the maximum opening times concludes that only the VT with a single FV would be able to pass most bridges outside of rush hours away from Amsterdam. With the failure of this feasibility check, the case route is not viable for the VT penetration into urban areas. For this to become viable, the route would have to cut short and the VT would have to separate for the final bridges.

Interviews with bridge operators revealed that most of the municipalities in the Netherlands pursue a policy that has a maximum of ten minutes bridge opening time per passage, *Backers (2020)*. This means there may be room to extend these passages slightly. With this extended time and a reduction in safety distance, a VT length of at most three FVs becomes possible.

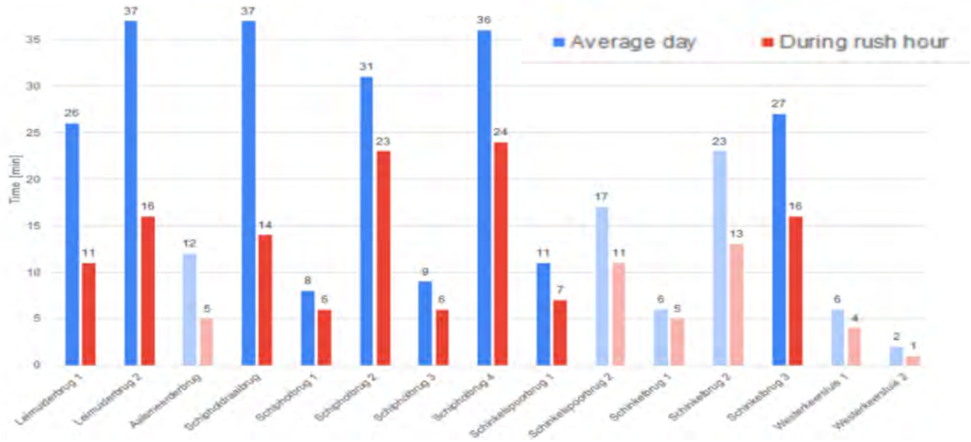

Fig.3: Maximum bridge opening times on an average day and at rush hour

4.3.2. Maximum number of bridges simultaneously open

Fig.2 showed that the bridges with opening limitations due to emergency services are 2, 3, 7, 8, 11, 12 and 13. Table III indicates the number of simultaneous bridge openings required per bridge section. When considering only a single FV, bridge sections seven and eight are the limiting factors, as the VT may not be able to pass in case of an emergency situation on the road. Longer VTs increase the simultaneous bridge opening up to five in the urban area of Amsterdam. Hence, the case study leading into Amsterdam is thereby also not passing the second feasibility check. This means that the FV crews will need to stay alert between bridge sections seven and eight to potentially decouple from the train, if the emergency road traffic causes the VT to get separated by the bridge.

Table III: Open bridges required per route section

Viable VT lengths	length (km)	Bridge sections																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 FV	0,62	1	1	1	1	2	1	3	2	1	2	2	1	1	1	2	2	3	3
3 FV	1,04	1	1	1	3	2	1	3	2	1	3	2	2	2	2	3	4	4	3
6 FV	1,67	1	1	1	3	2	1	4	3	2	4	3	3	3	4	5	5	4	3

4.3.3. Congestion improvement

One of the goals of this research is to identify how much congestion cost-benefit the VT would be able to achieve. Even though the feasibility checks, that would ensure seamless VT-bridge passage, were not met, it is still worth gauging the magnitude of the potential congestion cost savings, as it can still be indicative for other routes with more appropriate bridge spacing's. It is hence useful to obtain an understanding of how large potential congestion cost savings could be. Before, presenting the congestion cost savings, the maximum VT length that is able to achieve these savings is shown in table IV. This is calculated based on Eq.(5) while solving for n. This length is determined for a variety of safety distances. It shows that all the economically viable VT lengths presented in the case study section can be accommodated. However, for this to be possible, the safety distance between the vessels needs to be 10% or less of the vessel length.

Table IV: Maximum number of FVs in VT based on safety distance between vessels

Safety distance	0.1	0.5	1	1.5
Max VT Length (LV + FVs)	7	6	5	4

The total annual hours of bridge opening time saved over the length of the route can vary from as high as 219 h with 3 FVs or 106 h with 1 FVs at 100% market share, to as little as 1 h saved with 3 FVs or 48 min with 1 FVs at 1% market share. Fig.4 translates these savings into monetary values for a range of different market shares. The bottom line represents the conditions in which all road traffic participants would be cars and the top line assumes all participants to be trucks. The maximum social congestion benefit has a range that lies in the green shaded area dependent on the composition of the road traffic. The maximum cost saving achieved for this route, in the best case savings scenario that all waiting traffic are trucks would be close to €0.8 million. Any results where the VT has a market share smaller than 25% are negligible. Given the fact that even VT implementation of 25% of the market share can be considered large, a realistic implementation of the concept with about 10% of the market share is not able to improve the VT case viability to penetrate urban areas.

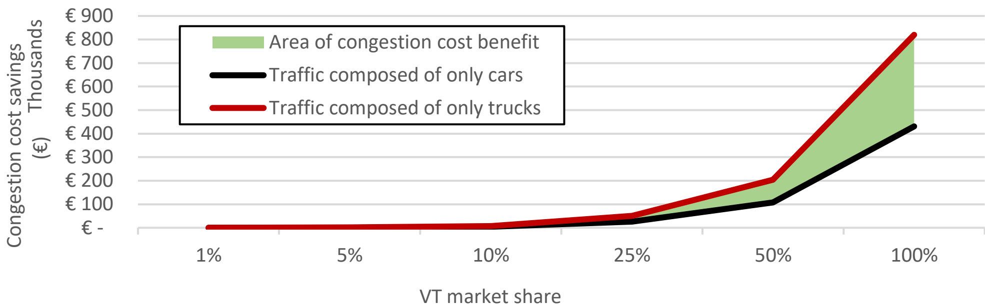

Fig.4: Congestion cost-benefit for different VT market shares

Based on the required number of participants for the VT liner service presented in *Colling et al. (2021)*, around 4000 passages are needed. These are more passages than the recorded annual cargo vessel passages for the route, Table I. However, if the other type of vessel, including recreational vessels are counted, the demand for the required number of vessel passages can be met, with the total passages reaching around 6000. This means that the theoretical market share of 66% of all participants, cargo and recreational vessel, would be needed to ensure economically viable VT operations to be achieved. This final observation lets us conclude that the route can only be considered as an addition to the VT operations and not as its main service, as that would mean the cargo flows on these smaller waterways need to be larger. Alternatively, the business model of the VT operator would also have to be adjusted such that other types of waterway users can take advantage of the VT services as well.

5. General guidelines for successful implementation of VTs in urban areas

The case study application showed that the metropolitan area of Amsterdam is a challenging target for the VT implementation. This is mainly due to the road traffic intensity and short road distances to intersections. However, this case study is not representative of all urban areas. It could actually be viewed as a worst-case scenario. Routes with less road traffic density would likely not fail at the bridge opening times feasibility check, but rather more likely at the number of simultaneous bridge openings.

The plots in Fig.5 are generic lookup keys that can provide guidelines to determine if a specific route can fit the requirements to pass the feasibility tests. The data accompanying these plots are provided in the appendix. The left plot provides bridge opening times based on various traffic conditions that can be crosschecked with the passage time of the desired VT length. This value can then be used in the right plot to determine if the bridge spacing along the route meets the minimum lengths. The right-hand key was explicitly set to accommodate vessel lengths of CEMT I-III, which are the vessel types sailing on smaller waterways in urban areas.

The minimum viable conditions from the lookup tables conclude that with an allowed traffic jam length of as short as 400 m, the maximum traffic intensity cannot surpass 550 vehicles per hour to ensure that at least a VT with one FV can pass. VTs composed of Class II vessels need a minimum bridge spacing of 400 m to ensure the passage of a VT with at least one FV.

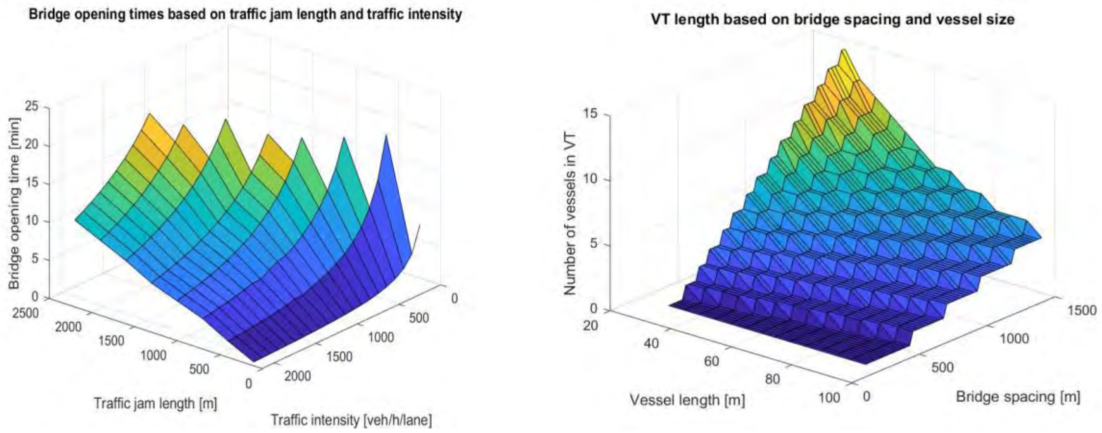

Fig.5: Generic lookup keys for VT penetration of urban areas

6. Conclusion

This paper presented the opportunities and challenges of applying semi-autonomous navigation to penetrate urban waterways with the VT concept. The model compares the road to the water traffic conditions and determines whether a given route is viable for the VT concept implementation. To demonstrate the application viability a route in the Dutch province of Noord- Holland is studied.

The main influence factors of urban penetration are: 1) Bridge opening time 2) Maximum number of simultaneous adjacent bridge openings. The bridge opening times are based on the traffic intensity and the road space to the next crossing in front of the bridge. The number of adjacent bridge openings is highly dependent on road-based emergency traffic that needs to reach its destinations without significant delays. Yet, a rule of thumb is that no more than two adjacent bridges should be opened simultaneously. The viability of the VT operations fitting into the distance between these bridge opernings is dependent on the geographical spacing of the bridges as well as the safety distances between vessels. Additionally, the VT operations would have to be targeted such that they fall outside of rush hours, yet still within the opening times of the bridges. Regulations such as the bridge operating hours or even the maximum individual opening times could be amended with a greater vessel demand, others such as the number of simultaneous bridge openings, are not likely to be changeable.

The case study between De Kaag and the port of Amsterdam has shown to be a challenging route for the seamless VT implementation and does not achieve viability for the entire route. In the metropolitan area of Amsterdam, the traffic on the road, even outside of rush hour, does not allow the bridges to be open for long enough to let a minimum VT of one FV pass together with the LV. It is however, expected that other urban areas may indeed achieve viability. This can be confirmed by cross-checking the general guidelines provided in this paper. The assessment of the congestion benefit showed that a maximum of €0.8 million could be achieved over this single route when clustering all cargo vessel to pass with at least one other vessel. Even larger savings can be expected if other vessel types are added to these clusters. The VT would at least require a participation of 25% of all cargo vessels passing for a noticeable congestion cost reduction to be achieved. Such a required fleet share is high for a target implementation of the VT concept.

The required number of passages concluded from the viability study by *Colling et al. (2021)* requires more vessel passages than the cargo vessels passages recorded along the route. This suggests that either the route can only be considered as an addition to the VT operations and not as the VTs main service route or other vessel types, potentially including recreational vessels, would have to be joining the train. The model developed within the research is used to provide generic lookup keys that can serve as guidelines to determine if another route could be suitable for the VT application.

Acknowledgement

The research leading to these results has been conducted within the NOVIMAR project (NOVel Iwt and MARitime transport concepts) and received funding from the European Union Horizon 2020 Program under grant agreement n° 723009. Thanks for sharing their knowledge and time on the topic of bridge passage go to: Sonja van Steekelenbrug and Bart Bosman from the province Noord-Holland, Guido op 't Hof who works on the Blauwe Golf bridge monitoring system, Robert van der Bor and Andries de Weerd who are skippers and Mike Backers who is a bridge operator.

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Appendix

Table V: Bridge data input data

Ref.	***Bridge name***	***Bridge Heights (m)***	***distance to next bridge (km)***	***annual number of average bridge openings for cargo***	***Road data vailability***
1	OudeWeteringbrug	**2,7**	2,24	**1568**	No data
2	Leimuiderbrug	**2,5**	7,32	**2615**	Available
3	Aalsmeerderbrug	**2,5**	5,37	**2125**	Available
4	Bosrandbrug	**1,4**	0,74	**1735**	No data
5	Schipholdraaibrug	**3,4**	0,13	**250**	Available
6	Schipholbrug (brug in A9)	**7,9**	3,28	1659	Available
7	Schinkelspoorbrug	**8,1**	0,03	1659	Available
8	Schinkelbrug (metrobrug)	**8,1**	0,03	1659	No data
9	Schinkelbrug (brug in A10)	**7**	1,6	1659	Available
10	Zeilstraatbrug	**2,7**	0,43	1659	No data
11	Theophile de Bockbrug	**2,5**	0,35	1659	No data
12	Overtoomsebrug	**2,4**	0,82	1659	No data
13	Kinkerbrug	**2,5**	0,7	1659	No data
14	Wiegbrug	**2,5**	0,68	1659	No data
15	Beltbrug	**2,9**	0,45	1659	No data
16	Van Hallbrug	**2,6**	0,47	1659	No data
17	Kattenslootbrug	**2,5**	0,4	1659	No data
18	Willemsbrug	**2,7**	0,1	1659	No data
19	Singelgrachtspoorbruggen	**6**	0,5	1659	Available

The red values of the bridge heights indicates that the bridge needs to open to let cargo vessels pass. The bold values of the average number of annual bridge openings for cargo vessels based on the available data from the bridge management system. All other values are the average of the available data.

Table VI: Available road traffic data

Ref.	Measurment point	Average day			Rush hour			Max jam length [km]
		Intensity [veh/h/lane]	Speed [km/h]	Vehicle length [m]	Intensity [veh/h/lane]	Speed [km/h]	Vehicle length [m]	
2	Leimuiderbrug, downstream, links	363	88	4,3	869	84	4,2	0,8
2	Leimuiderbrug, upstream, links	328	79	4,5	806	30	4,0	1,0
3	Aalsmeerderbrug, downstream, links	186	84	4,3	508	88	4,0	0,2
5	Schipholdraaibrug, upstream, links	189	74	5,9	643	71	4,6	0,8
6	Schipholbrug, downstream, rechts	798	93	4,6	1223	71	4,2	0,6
6	Schipholbrug, upstream, rechts	1000	95	4,6	1463	85	4,2	2,7
6	Schipholbrug, upstream, links	809	88	4,6	1250	68	4,2	0,6
6	Schipholbrug, downstream, links	875	96	4,6	1360	84	4,2	2,7
7	Schinkelspoorbrug, upstream, links	1132	79	4,6	1798	60	4,2	1,1
7	Schinkelspoorbrug, downstream, rechts	1224	87	4,6	1897	74	4,2	1,8
9	Schinkelbrug, downstream, links	1621	86	4,6	2138	75	4,2	0,9
9	Schinkelbrug, downstream, links	909	92	4,6	1702	78	4,2	1,8
9	Schinkelbrug, upstream, rechts	972	91	4,6	1714	78	4,2	2,3
19	Westerkeersluis, downstream, links	438	59	4,2	772	56	4,3	0,2
19	Westerkeersluis, upstream, links	356	54	4,2	650	52	4,1	0,1
	Average	746,6	83,0	4,6	1253	70,3	4,2	1,2

Assumptions made for this data:

- During the day, all the lanes except for the emergency lanes were used. Only during rush hour, all the lanes including the emergency lanes were used for traffic.
- The data only consist of working days, weekends and public holidays were excluded

Table VII: Bridge opening times (min) dependent on road traffic

intensity [veh/h/lane]	maximum traffic jam size [m]							
	100	400	700	1000	1300	1600	1900	2200
150	8,4	33,8	56,1	92,2	97,0	126,7	195,4	221,5
250	5,0	19,6	33,9	53,2	57,7	74,4	110,2	125,4
350	3,5	14,2	24,3	37,1	41,0	52,4	75,6	86,2
450	2,7	11,0	19,2	28,3	31,8	40,4	57,1	65,1
550	2,2	8,9	15,6	22,8	25,9	32,8	45,6	52,1
650	1,9	7,5	13,1	19,0	21,9	27,5	37,8	43,2
750	1,6	6,5	11,3	16,3	18,9	23,7	32,2	36,9
850	1,4	5,7	9,9	14,3	16,6	20,8	28,0	32,1
950	1,3	5,1	8,8	12,7	14,9	18,5	24,7	28,3
1050	1,1	4,5	7,9	11,4	13,4	16,7	22,1	25,3
1150	1,0	4,1	7,2	10,3	12,2	15,2	20,0	22,9
1250	1,0	3,6	6,9	9,4	11,2	13,9	18,2	20,9
1350	0,9	3,6	6,3	8,7	10,4	12,9	16,7	19,2
1450	0,8	3,3	5,6	8,0	9,7	11,9	15,4	17,7
1550	0,8	3,0	5,6	7,5	9,0	11,1	14,3	16,4
1650	0,7	2,9	5,2	7,0	8,5	10,4	13,3	15,4
1750	0,7	2,7	4,9	6,6	8,0	9,8	12,5	14,4
1850	0,6	2,5	4,7	6,2	7,6	9,3	11,7	13,5
1950	0,6	2,4	4,4	5,8	7,2	8,8	11,0	12,8
2050	0,6	2,3	4,2	5,5	6,8	8,3	10,4	12,1
2150	0,5	2,2	4,0	5,3	6,5	7,9	9,9	11,4

Green: allows viability for all VTs; Orange: allows conditions for viable trains with three to six FVs (assuming safety distance of 1,5); Yellow: allows minimum viable conditions of one FV to be met; Red: Not viable

Table VIII: Maximum viable VT lengths dependent on vessel sizes and minimum bridge distances

	Average vessel length [m]													
Minimum bridge spacing [m]	35	40	45	50	55	60	65	70	75	80	85	90	95	100
100	1	1	1	1	1	1	1	1	1	1	1	1	1	1
125	1	1	1	1	1	1	1	1	1	1	1	1	1	1
150	1	1	1	1	1	1	1	1	1	1	1	1	1	1
175	1	1	1	1	1	1	1	1	1	1	1	1	1	1
200	1	1	1	1	1	1	1	1	1	1	1	1	1	1
225	2	1	1	1	1	1	1	1	1	1	1	1	1	1
250	2	2	1	1	1	1	1	1	1	1	1	1	1	1
375	2	2	2	2	1	1	1	1	1	1	1	1	1	1
300	2	2	2	2	2	1	1	1	1	1	1	1	1	1
325	3	2	2	2	2	2	1	1	1	1	1	1	1	1
350	3	3	2	2	2	2	2	2	1	1	1	1	1	1
375	3	3	3	2	2	2	2	2	2	1	1	1	1	1
400	4	3	3	3	2	2	2	2	2	2	2	1	1	1
425	4	3	3	3	2	2	2	2	2	2	2	2	1	1
450	4	4	3	3	3	2	2	2	2	2	2	2	2	2
475	4	4	3	3	3	3	2	2	2	2	2	2	2	2
500	5	4	4	3	3	3	3	2	2	2	2	2	2	2
525	5	4	4	4	3	3	3	3	2	2	2	2	2	2
550	5	5	4	4	3	3	3	3	3	2	2	2	2	2
575	6	5	4	4	4	3	3	3	3	2	2	2	2	2
600	6	5	5	4	4	3	3	3	3	3	2	2	2	2
625	6	5	5	4	4	4	3	3	3	3	3	2	2	2
650	6	6	5	5	4	4	3	3	3	3	3	3	2	2
675	7	6	5	5	4	4	4	3	3	3	3	3	3	2
700	7	6	5	5	4	4	4	4	3	3	3	3	3	3
725	7	6	6	5	5	4	4	4	3	3	3	3	3	3
750	8	7	6	5	5	4	4	4	4	3	3	3	3	3
775	8	7	6	6	5	5	4	4	4	3	3	3	3	3
800	8	7	6	6	5	5	4	4	4	4	3	3	3	3
825	8	7	7	6	5	5	5	4	4	4	4	3	3	3
850	9	8	7	6	6	5	5	4	4	4	4	3	3	3
875	9	8	7	6	6	5	5	5	4	4	4	4	3	3
900	9	8	7	7	6	5	5	5	4	4	4	4	3	3
925	10	8	7	7	6	6	5	5	5	4	4	4	4	3
950	10	9	8	7	6	6	5	5	5	4	4	4	4	4
975	10	9	8	7	6	6	5	5	5	4	4	4	4	4
1000	10	9	8	7	7	6	6	5	5	5	4	4	4	4
1025	11	9	8	8	7	6	6	5	5	5	4	4	4	4
1050	11	10	9	8	7	6	6	6	5	5	5	4	4	4
1075	11	10	9	8	7	7	6	6	5	5	5	4	4	4
1100	12	10	9	8	7	7	6	6	5	5	5	5	4	4
1125	12	10	9	8	8	7	6	6	6	5	5	5	4	4
1150	12	11	9	9	8	7	7	6	6	5	5	5	5	4
1175	12	11	10	9	8	7	7	6	6	5	5	5	5	4
1200	13	11	10	9	8	7	7	6	6	6	5	5	5	5
1225	13	11	10	9	8	8	7	7	6	6	5	5	5	5
1250	13	12	10	9	8	8	7	7	6	6	6	5	5	5
1275	14	12	11	10	9	8	7	7	6	6	6	5	5	5
1300	14	12	11	10	9	8	7	7	7	6	6	5	5	5
1325	14	12	11	10	9	8	8	7	7	6	6	6	5	5
1350	14	13	11	10	9	8	8	7	7	6	6	6	5	5
1375	15	13	11	10	9	9	8	7	7	6	6	6	5	5
1400	15	13	12	11	10	9	8	8	7	7	6	6	6	5

Red: not VT viable; Blue: a mature VT economically viable; Dark blue: early state VT economically may be viable dependent on the operating regime of the reference vessel; Green: VT is viable for most conditions

Parametric Modeling and Hydrodynamic Optimization of an Electric Catamaran Ferry based on Radial Basis Functions for an Intuitive Set-up

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Abstract

The paper presents a design study for an electric catamaran ferry undertaken at the tender stage. Starting from a baseline created to comply with the operational requirements of the future owner, a parametric modeling and hydrodynamic optimization campaign was conducted with the aim of further reducing energy consumption as much as possible, the weight of batteries and the range of a purely electric ferry being of key importance. Due to the short time available in early design, here just three weeks, a partially-parametric modeling approach using Radial Basis Functions was selected. The ferry being relatively short despite considerable displacement when fully loaded and the clearance of the demi-hulls being small, a free-surface RANS code with free trim and sinkage was employed for the hydrodynamic optimizations. The practical approach of modeling and optimization will be explained and illustrated. Results for several displacements at different speeds will be presented, showing the tangible improvement realized within a highly concerted team effort.

1. Introduction

The maritime industry steadily gains momentum in introducing new ways of providing boats and ships with clean(er) energy. For more than a century the main source of energy for shipping came first in form of coal and then in form of fuel oils. While this will likely continue for quite some time, with steady improvements in engine efficiency and (transition) technologies such as gas engines made available, more and more projects are worked on that are built on purely electric propulsion. Electric ferries for relatively short distances have turned out to be good candidates for early adaptation. They allow full charging of batteries during the nights when in port and intermediate recharging of batteries when (un)loading, see *Jokinen et al. (2021)*.

The project presented in this paper focuses on the hydrodynamics of a small passenger ferry for transfer between two ports, covering a short distance of a little less than one sea mile. Typically, a ferry of only about 12 m in length-over-all and 21 t of maximum displacement would not necessarily undergo a thorough hydrodynamic optimization campaign, in particular if intended to be run on standard fuel. However, batteries still being expensive and pretty heavy due to lower energy density in comparison to, say, diesel, the effort could be justified. As will be seen the improvements are considerable which may serve to encourage similar studies in the future, see also *Albert et al. (2016)* and *Albert et al. (2020)* for applications of simulation-driven design (SDD) to small craft.

The paper presents the design task, then covers the chosen parametric modeling approach, namely Radial Basis Functions (RBF) with focus on an intuitive set-up, and subsequently elaborates on the viscous flow simulations. The optimization approach, including a Design-of-Experiment, surrogates and multi-objective optimizations, will be discussed, finishing with a comparison of results for both the baseline and the best variants identified. The systems used for the campaign were CAESES® for parametric modeling, FINE™/Marine for RANS simulations and FINE™/Design for optimization. The project is considered to be representative of good SDD practice and hopefully serves less experienced design teams to develop a deeper understanding.

2. Design task

Yachtwerft Meyer, Germany, a specialist for tenders of yachts and cruise ships as well as for special crafts (police and coast guard vessels, rigid inflatable boats etc.) and with strong expertise in composite materials, assumed the leading role as designers while FRIENDSHIP SYSTEMS and NUMECA Ingenieurbüro contributed their expertise of geometric modeling and numerical flow simulation, respectively.

Fig.1 shows the hull of the catamaran ferry, featuring a skeg for a classical propulsion system with shaft, propellers and spade rudders (not shown). The specifications of the ferry as relevant for the hydrodynamic optimizations were taken from the owner's requirements and are summarized in Table I. Various criteria such as stability were not explicitly monitored during the optimizations as they were sufficiently fulfilled for the baseline and not too strongly affected by the form variations considered.

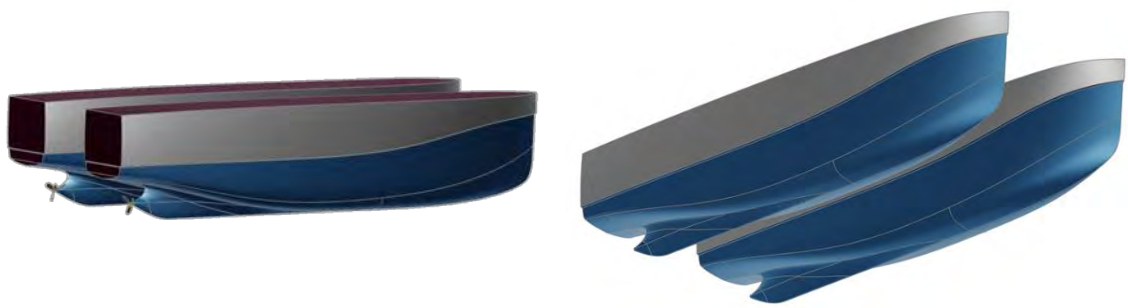


Fig.1: Hull form of electric catamaran ferry (baseline)

Table I: Specification of hydrodynamic design task

Passenger ferry	Catamaran with classical propulsion system
Maximum capacity	60 passengers with luggage
Displacement at max. capacity	21 t
Displacement at min. capacity	14 t
Length	~ 11.5 m
Max. beam over all	4.7 m
Draft	~ 1 m
Design speed	7.0 kn for major leg
Representative lower speed	3.5 kn in port
Distance to cover	~1 nm between ports
Additional criteria	Spray rails should not submerge at max. draft
Battery size	6 × 40 kWh @ 360 V
Battery capacity	Sufficient for 20 runs when fully charged

The aim of the optimization campaign was to reduce energy consumption as much as possible while maintaining maximum passenger capacity. A preliminary study for the two speeds of interest, namely design speed of 7 kn and a representative speed in port of 3.5 kn, showed that more than 80% of battery power would be consumed at the higher of the two speeds when covering the major leg between ports (see also resistance at different speeds given in the result section). Since the operational profile suggested frequent transfers at (close to) maximum and (close to) minimum capacity the resistance at both displacements was taken into account and a multi-objective design task was formulated.

The focus was set on minimizing resistance. This is because the optimization campaign was undertaken during the rather short tender stage as an investment of the bidding party and, furthermore, could be technically justified on the grounds that the skeg geometry was not varied but only adjusted to attach nicely to the bare hull. An unaltering skeg would result in similar wake patterns for all variants investigated. Hence, the propulsive efficiency was assumed to be practically constant. This, naturally, is a simplification. However, if the building order was won further optimizations could be initiated very quickly with additional free variables for both the bare hull and the skeg and for energy consumption as the ultimate objective, using propulsive power instead of resistance.

3. Parametric modeling

Optimizations are typically run to increase the energy efficiency of fluid-dynamically relevant shapes. The process is called simulation-driven design and requires a considerable number of variants to be investigated by means of simulations, notably by Computational Fluid Dynamics codes (CFD). Parametric modeling for the design and optimization of ship hulls, propellers, appendages etc. is now widely accepted and applied in both academia and industry. To balance intelligently a meaningful range of shape variations and a small enough set of free variables to control them, different approaches of parametric modeling have been developed, see *Harries (2020)* for an overview.

In SDD these Computer Aided Design approaches (CAD) are typically subdivided into fully-parametric and partially-parametric modeling. While fully-parametric modeling (FPM) is more powerful with regard to the scope and the precision of achievable modifications, partially-parametric modeling (PPM) is easier and faster to set up and handle. The range of available partially-parametric modeling approaches is considerable, and they all have advantages and drawbacks, see, for instance, *Harries et al. (2015)* and *Harries and Abt (2019)*. FPM and PPM can be flexibly combined in dedicated CAD systems like CAESES.

3.1. Partially-parametric modeling

Free-form deformation, cartesian shifts, Lackenby transformation etc. are used when changing a given baseline via parameters. These techniques have one common denominator: Based on an existing baseline, typically modeled interactively and then interpreted as a “dead” geometry, the way of modifying the shape (and not the shape itself) is defined parametrically. The actual modifications are then computed from imposing the modifying entities onto the baseline. While this is very flexible the actual variations are not predefined but rather “just” anticipated.

There are two partially-parametric modeling approaches that follow a slightly different idea: morphing and radial basis functions (RBFs). Here the new shapes are defined upfront by the design team and the partially-parametric modeling approach subsequently brings about a smooth transition between the baseline as a “source” and one or several of the predetermined shape features as “targets.”

Standard morphing builds on a set of topologically identical but geometrically different instances. With just two instances a one-dimensional design space is created, allowing the transition (interpolation) from one instance to the other and even beyond (extrapolation). Using three instances gives a two-dimensional design space and so on. See *Harries et al. (2015)* for details.

Radial basis functions offer a very intuitive set-up of defining modifications and can be considered a morphing approach in its broader sense. (It should be noted that quite frequently the term morphing is used for most partially-parametric modeling approaches.) In CAESES two RBF techniques are available: A discrete approach for interactively changing point data (trimeshes) and a continuous approach for changing mathematically-closed geometries represented by B-splines (BReps), see also *Harries and Abt (2021)*. For the catamaran optimization presented here the continuous approach was chosen since it allows the design team a fine-tuned modification of various regions that are likely to influence the hydrodynamic performance positively.

3.2. Radial Basis Functions

Before showing how the modifications were set up and applied to the catamaran ferry the mathematics of the RBFs shall be briefly discussed. The implementation in CAESES follows *Botsch and Koppelt (2005)*.

In general, RBFs are used for scattered data interpolation. For partially-parametric modeling in particular, a vector-valued space deformation is determined which yields the new position of any point in space. The deformation at any point

$$\vec{x}$$

of interest is defined as follows:

$$\vec{d}(\vec{x}) = \sum_j \vec{w_j} \cdot \varphi_j\,(\vec{x}) + \vec{p}(\vec{x})$$

where

$$\varphi_j(\vec{x}) = \left|(\vec{x} - \vec{c_j})^3\right|.$$

are the triharmonic Radial Basis Functions and

$$\vec{p}(\vec{x})$$

is a trivariate quadratic polynomial. The weights

$$\overrightarrow{w_j}$$

are computed to smoothly interpolate a set of pre-described displacements, introduced via a set of control points

$$\vec{c_j}$$

that are either fixed or deliberately displaced, preferably via parameters governing the displacements.

In CAESES a space deformation can be applied either to points on the geometry, as is done for trimeshes (discrete), or to the vertices of a B-spline representation (continuous). The set of control points is taken from sources, targets and fixed points. Sources are geometric entities like points, curves and surfaces that describe regions which are to be varied while targets are geometric entities of the same type that define the new shapes to which the geometry should smoothly adapt. Curves and surfaces are utilized to conveniently define larger sets of points that serve as input to the RBF computation.

Sources and targets have to be matching pairs, i.e., a point used as a source would need another point as a target, a curve used as a source would need a target curve as its counterpart and so forth. In addition, regions of transition need to be selected at which no modifications ought to take place. Finally, all entities that shall be subjected to the space deformation are selected.

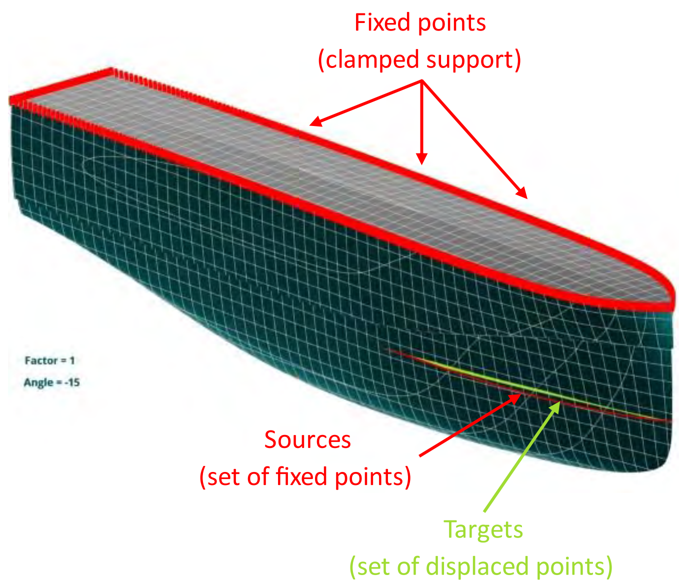


Fig.2: Radial Basis Function set-up for catamaran's bare hull
(the hull shown in dark green has received a modification according to the sources and targets)

Fig.2 illustrates this for the demi-hull of the catamaran ferry: The curve given in red describes the design waterline of the forebody and is used as (one of) the source(s). The curve given in green defines the new shape of the design waterline and is considered (one of) the target(s). The fixed points, also shown in red, are distributed along the transition between the hull and the deck. The hull, shown in dark green, is allowed to vary while the deck, shown in grey, is not subjected to the space deformation. (For a better appreciation one can think of the deck as a clamped support.) As can be seen the design waterline is slightly slimmer for the target as it is for the source. Consequently, the hull becomes slightly slimmer in the forebody, too, with a smooth transition to regions where no changes have been imposed and, naturally, no changes at all where the fixed points are located.

In principle, two options of controlling variations when applying the RBFs are offered within CAESES:

1. A true morphing in which a transition factor for interpolation (possibly extrapolation) from the baseline to the new shape is varied while keeping the targets constant, Fig.3.
2. A variation via parametrically changing the targets and using a constant transition factor, Fig.4.

A combination of the two options is supported, too, even though the true origin of a modification (and how to control it) may become a bit less obvious.

3.3. Sources and targets for intuitive variation

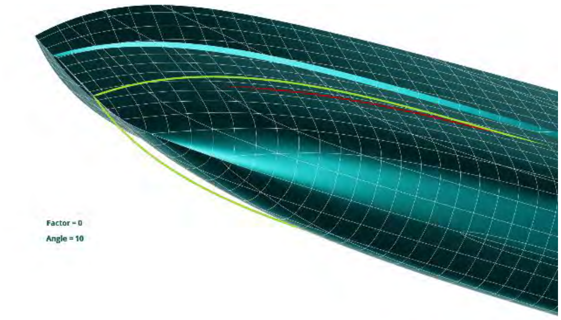
For the catamaran ferry option 2 was selected, using points and curves that were parametrically defined as targets, giving rise to eight free variables from RBFs and two additional free variables from standard transformations, namely a scaling of the cat's demi-hull in transverse direction and a change of the clearance between the two demi-hulls.

Based on the bare demi-hull designed by the yard the optimization campaign comprised setting up sources and targets for variation, preparing the geometry for hydrodynamic analysis and undertaking the actual optimization runs. The workflow is summarized in Table II. Fig.5 illustrates some of the steps.

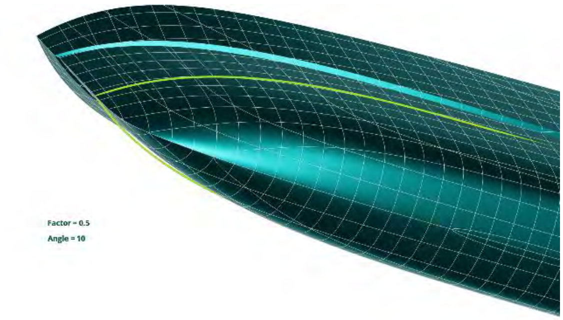
Table II: Workflow

Step	Description
1	Import baseline into CAESES® (e.g. STEP, iges)
2	Prepare baseline for variation (e.g. add transom and deck)
3	Define sources and targets to compute corresponding RBFs, introducing free variables
4	Apply changes according to free variables and generate variant of the demi-hull without skeg
5	Attach (fully-parametric) skeg to bare demi-hull
6	Merge new variant with flow domain
7	Export flow domain with new variant for FINE™/Marine (here as multi-body stl-file)
8	Set up FINE™/Marine for investigation
9	Run design-of-experiment with FINE™/Design3D
10	Build surrogate model for further optimizations
11	Run optimizations with FINE™/Design3D, adding CFD simulations for better predictions
12	Discuss results with all parties involved and repeat parts of the process

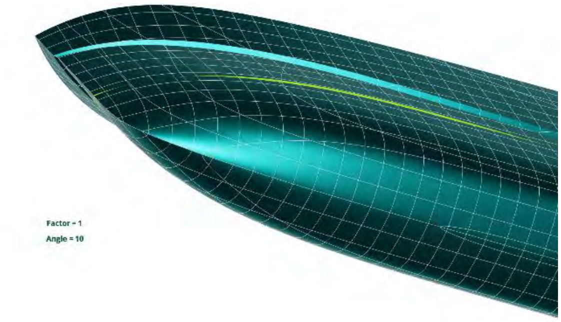
As can be seen from Fig.5 (E) and (F), here only points and curves were used for defining the sources and targets. The entities are chosen according to their expected impact on calm-water hydrodynamics, namely changing the design waterline (see also Fig.4), the stem contour, including the introduction of an asymmetry in the forebody, the center plane curve and the characteristic of the transom. In this sense the resulting scope of shape variations is rather intuitive and easy to set up.



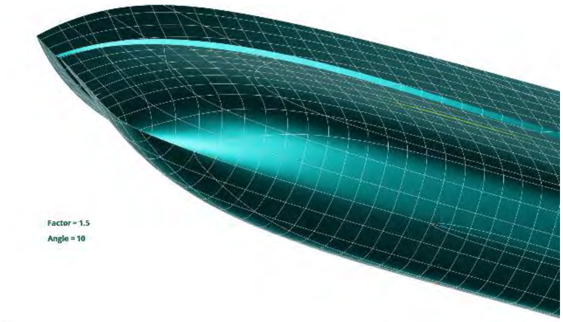
(A) Transition factor equal to 0 yields the baseline (sources)



(B) Transition factor equal to 0.5 yields an interpolation between the baseline and the target

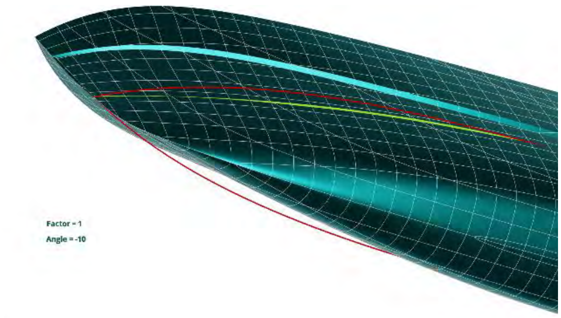


(C) Transition factor equal to 1 results in matching the target

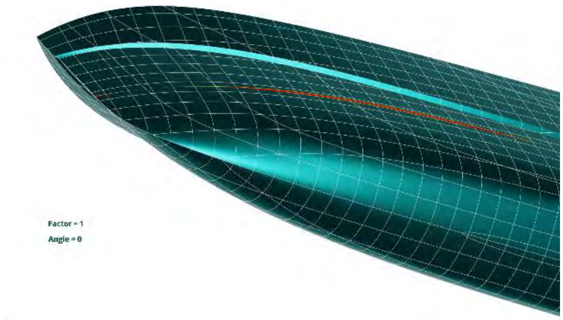


(C) Transition factor equal to 1.5 gives an extrapolation, going beyond the target

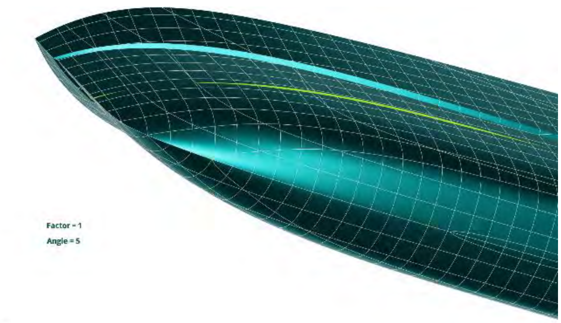
Fig.3: True morphing on the basis of RBFs with varying transition factor (but constant sources and targets)



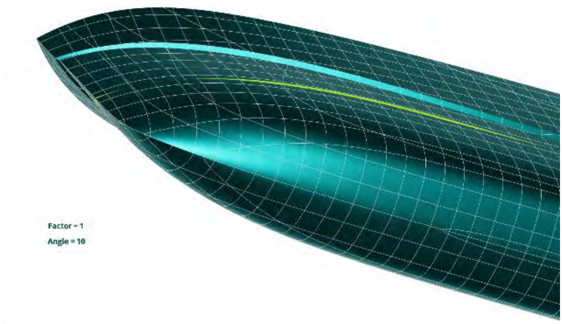
(A) Decreasing the entrance angle of the design waterline by 10°



(B) No change (targets match sources) yields the baseline

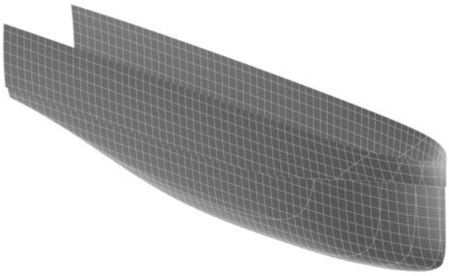


(C) Increasing the entrance angle of the design waterline by 5°

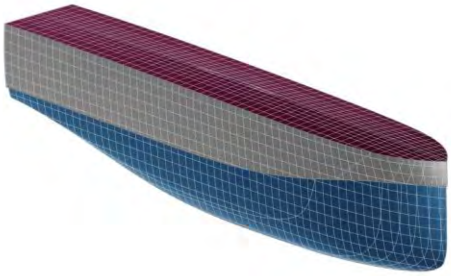


(D) Increasing the entrance angle of the design waterline by 10°

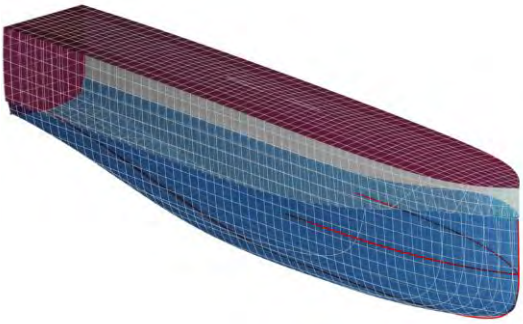
Fig.4: Variation via parametrically changing targets (with constant transition factor set to 1)



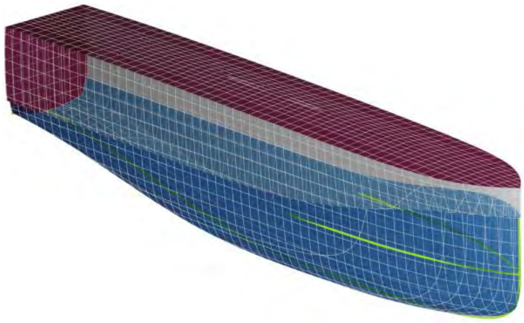
(A) Bare symmetric demi-hull as provided by yard
(see Table II step 1)



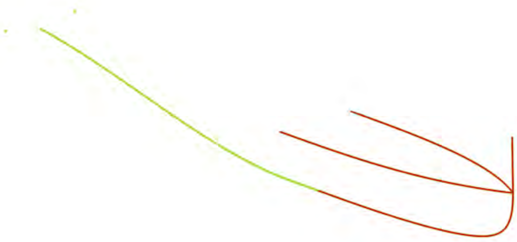
(B) Additions of deck and transom for closing geometry
(preparation stage, see Table II step 2)



(C) Define source(s), here shown in red, for the design
waterline of the baseline (see Table II step 3)

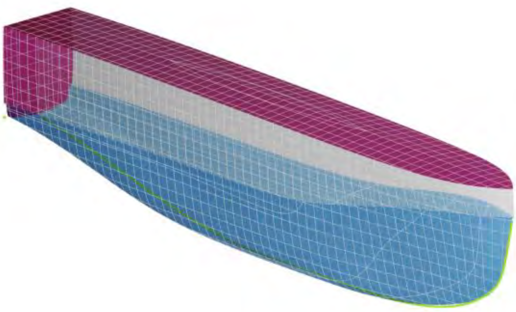


(D) Define target(s), here shown in green, for the
modification as anticipated to be beneficial
(see Table II step 3)

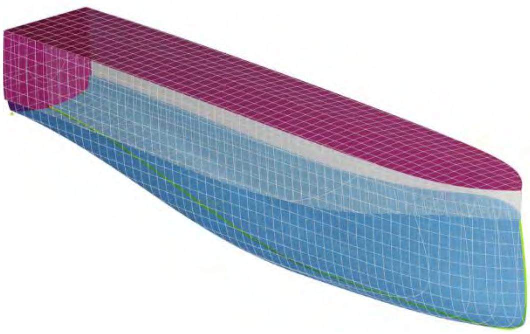


(E) Sources and targets match
(causing no changes to the geometry)

(F) Sources and targets differ
(giving rise to variation of geometry, see Table II step 4)



(G) Resulting variant for all free variables set to their
minimum values (see Table II step 4)

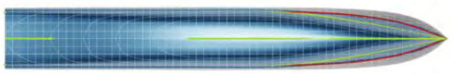


(H) Resulting variant for all free variables set to their
maximum values (note the asymmetry of the demi-hull)

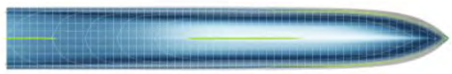
Fig.5: Stages of preparing and setting up partially-parametric modeling with RBF

3.4. Parametric model and example variations

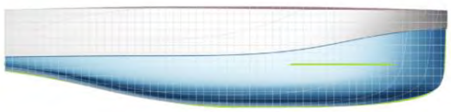
A partially-parametric model with a total of 10 free variables was defined as illustrated in Fig.6 and summarized in Table III.



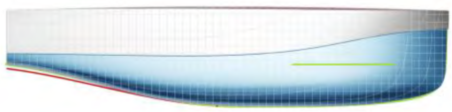
(A) deltaEntranceAngle set to lower bound



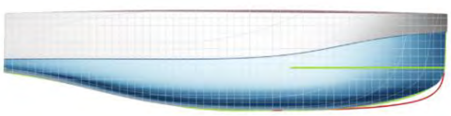
(B) deltaEntranceAngle set to upper bound



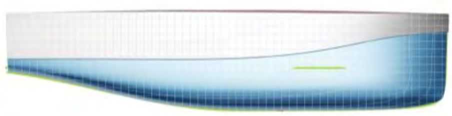
(C) deltaZtransom set to lower bound



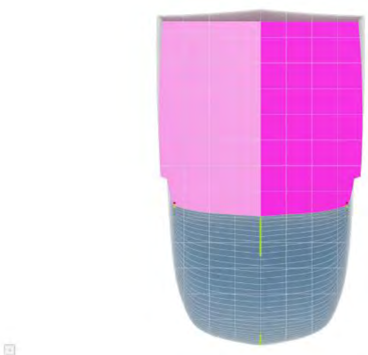
(D) deltaZtransom set to upper bound



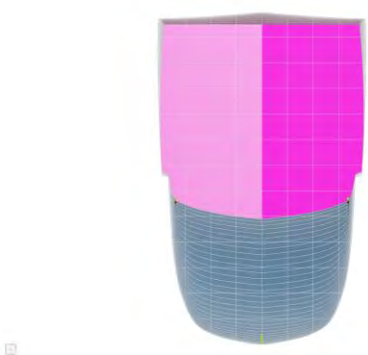
(E) stemFullness set to lower bound



(F) stemFullness set to upper bound



(G) changeDeadrise (of transom) set to lower bound



(H) changeDeadrise (of transom) set to upper bound

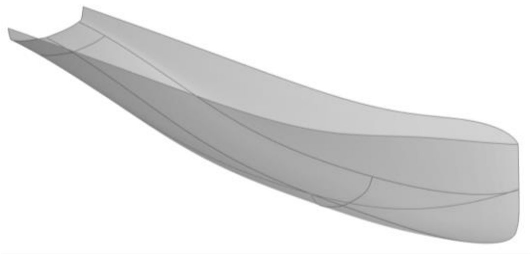
Fig.6: Selected variants by changing one free variable at a time

Table III: Parameters used as free variables

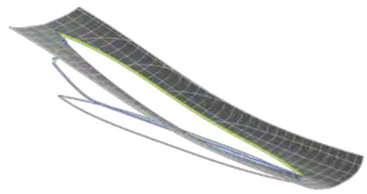
Step	Primary region of influence	Name	Description	See also
1	CPC	deltaAngleCPCtransom	Modify the angle of the center plane curve at the transom (aft perpendicular)	Figure 5 (F)
2		deltaParallelMid	Increase or decrease the length of the parallel mid-body	Figure 5 (F)
3		deltaZtransom	Control the submergence of the transom	Figure 6 (C) and (D)
4		stemAngle	Change from a vertical to a tilted stem	Figure 5 (F)
5		stemFullness	Increase or decrease fullness of stem	Figure 6 (E) and (F)
6	DWL	asymmetricBow	Introduce asymmetry to the forebody	Figure 5 (H)
7		deltaEntranceAngle	Increase or decrease the entrance angle of the DWL at the forward perpendicular	Figure 6 (A) and (B)
8	General	changeClearance	Widen or narrow the clearance between the demi-hulls	
9		scaleY	Scale demi-hull in transverse direction	Figure 8 (A) and (B)
10	Transom	changeDeadrise	Push up or pull down transom close to sharpest rounding	Figure 6 (G) and (H)

3.5. Adding the skeg

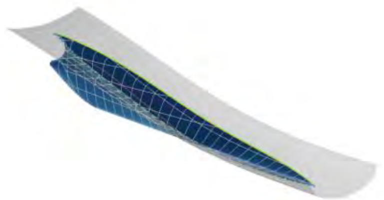
As soon as a new variant of the bare hull is available it is brought together with a skeg as shown in Fig.7. Since during the optimization campaign the bare hull also varies with regard to beam, the center plane curve and the transom, it does not suffice to simply attach one given skeg. Instead a number of defining curves are modeled from which to derive the skeg as a Gordon surface, see Fig.7 (B), giving rise to a smooth transition between the bare hull and the skeg itself.



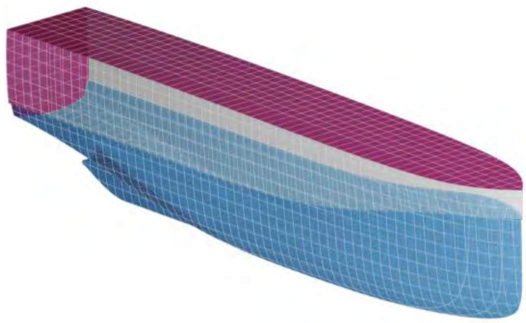
(A) Parts of the bare hull after transformation via RBF



(B) Definition of the skeg via boundary curves



(C) Skeg defined as a Gordon surface



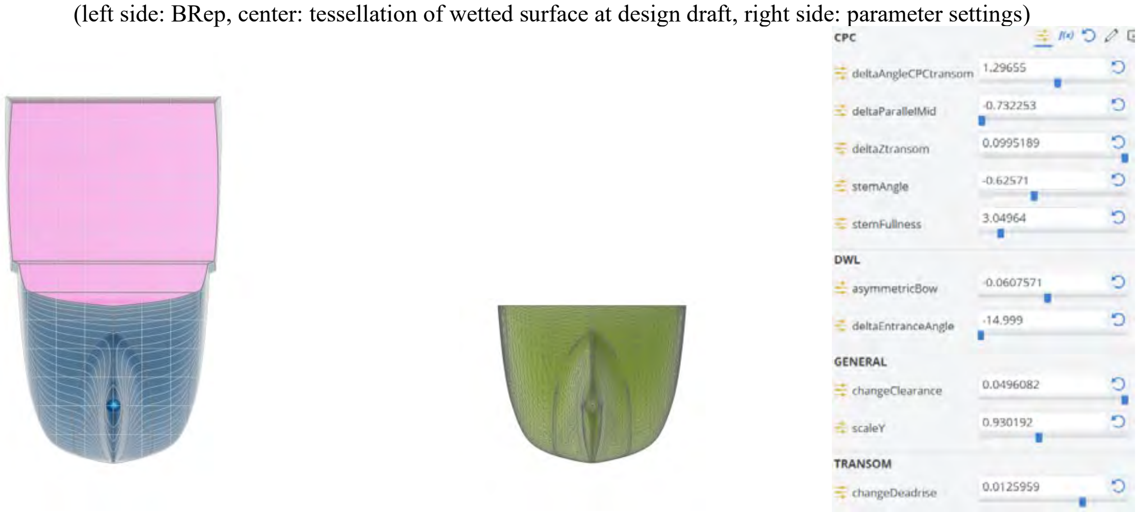
(D) BRep model of entire demi-hull (see Table II step 5)

Fig.7: Stages of adding a skeg to the bare hull

Four prominent curves are defined which are the circular bossing, an upper cut-away curve in the center plane, a lower planar curve from the keel line to the bossing (shown in blue in Fig.7 (B)) and a curve on the bare hull’s surface (shown in green in Fig.7 (B)) which is derived from a vertical projection of a planar contour (shown in grey in Fig.7 (B)). These four curves would already define a Coons Boolean surface patch. In order to further increase the quality of the resulting skeg, two additional space curves were prescribed that each start and end at opposing boundary curves and that intersect in the middle. This gives rise to a smooth mesh of six defining curves which then serve as input to a fully-parametric Gordon surface. (It may be worthwhile to note that the final boundary representation (BRep) of the demi-hull consequently results from a hybrid definition, using a partially-parametric modification of a baseline for the bare hull via RBFs and a fully-parametric definition of the skeg.)

For the optimization campaign the position and radius of the circular bossing and shape of the lower planar curve from the keel line to the bossing were kept constant. The upper cut-away curve would naturally adjust to the bare hull as would the space curve from the projection of the constant planar contour onto the bare hull, giving a good compromise between a comparable skeg geometry for all variants and a smooth transition between the different regions, see Fig.8.

(A) Baseline with skeg
(left side: BRep, center: tessellation of wetted surface at design draft, right side: parameter settings)



(B) Optimized hull with skeg
(left side: BRep, center: tessellation of wetted surface at design draft, right side: parameter settings)

Fig.8: Baseline vs. optimized hull (variant 101) along with their corresponding parameter settings

4. RANS simulations on the base design

NUMECA's FINE™/Marine package was used for the viscous CFD calculations, utilizing a volume-of-fluid (VOF) method for free surface capturing, see *Queutey and Visonneau (2007)*. The numerical representation and accuracy of the time-dependent free surface is strongly affected by the spatial discretization in the grid, especially perpendicular to the air-water-interface. FINE™/Marine features an adaptive grid refinement (AGR) technique which can create or remove mesh cells during solver runtime, triggered by various physical phenomena. Here the current location of the free surface acts as the sensor and the mesh is refined until a user-specified threshold in terms of the cell size is achieved. This procedure is called in certain intervals and ensures an ideal grid at all locations and at all time steps. Such an approach does not require any pre-refined mesh zones where the user would need to anticipate important phenomena in the flow field beforehand, e.g. wave patterns and regions of breaking waves. During an optimization with variable geometry and for two different displacements, which on their own strongly affect the location of the free surface, an AGR thus reduces the necessary CPU time for each variant investigated. Furthermore, an integrated body motion solver couples the hydrodynamic loads on the structures of interest with their inertia, see *Leroyer and Visonneau (2005)*, which is an important factor especially for smaller craft like the catamaran ferry.

The typical starting point for any optimization campaign is a detailed analysis of the baseline, the set-up of a smooth workflow and the investigation of possible numerical sensitivities like boundary conditions and grid resolution. The aim of the project was a reduction of total resistance for the wetted hull, including the lower parts of the freeboard. The superstructure was not taken into account. This is a valid approach since especially for low operating speeds air drag is rather small and even in rough weather the variation of the hull should have only negligible effect on the flow about the superstructure. The cat was supposed to run straight ahead in calm seas, solving for sinkage and trim for the two displacement conditions.

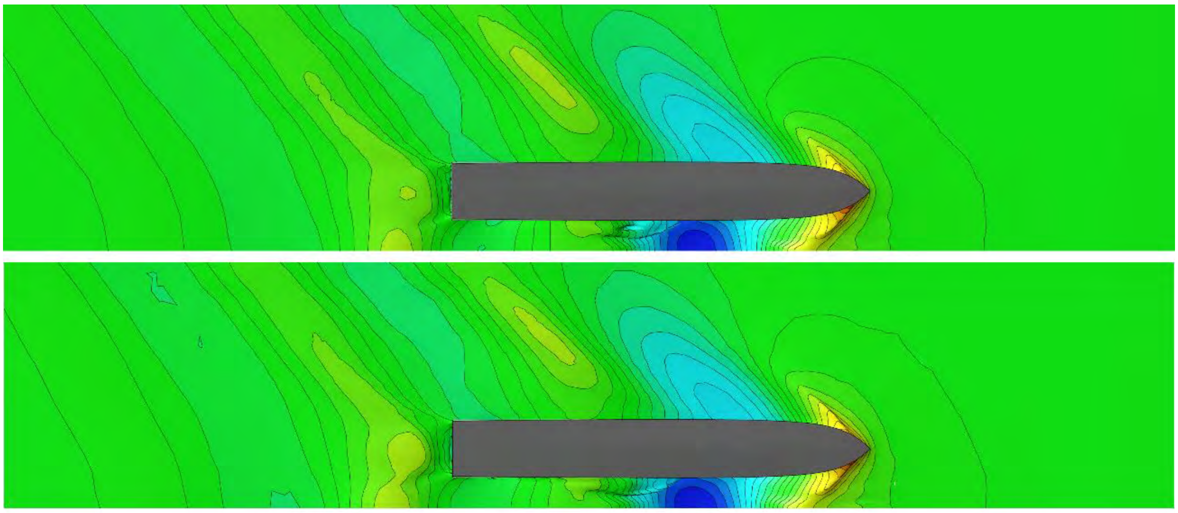
The flow was readily simulated at full-scale, taking advantage of running at both the correct Froude and Reynolds numbers without any need for model-ship extrapolations. Such a resistance simulation can be handled fully automatically using the C-Wizard in FINE™/Marine, which provides meshing templates for various densities as well as the full solver set-up. In conjunction with the stable yet flexible STL file export from CAESES® this ensures a smooth workflow, yielding preliminary results after just two hours of exchanging the baseline geometry. For the set-up of a suitable flow domain and the exchange of data between CAESES® and FINE™/Marine via STL files see *Albert et al. (2016)* for details. Importantly, within CAESES the topology of the flow domain along with the colors and name tags assigned to various parts of the domain (e.g. inner hull, outer hull, spray rail, deck, transom etc.) stay unaltered during any variation. Hence, when exporting them in a multi-body STL file FINE/Marine can readily handle any new variant without manual interaction.

As a next step a grid resolution study and further sensitivity tests were undertaken. The results for the free surface elevation at 7 kn and 21 t are given in Fig.9 (A) for both a rather fine and a coarser mesh. The wave patterns are very similar, especially for the extrema at the bow and in the tunnel between the demi-hulls which have a major impact on the overall resistance. The total resistance computed with the two meshes differ only by about 10 N. This is insignificant for a total resistance of 4372 N that the baseline displayed, see also Fig.10. Apart from being much smaller than the anticipated improvements, see also Fig.15, it can also be assumed that similar deviations would occur for all variants. Naturally, no changes of the set-up take place during an individual optimization run. As a sidenote, all resistance values given in this work were averaged over the last 30% of simulation time to smoothen out possible local flow unsteadiness.

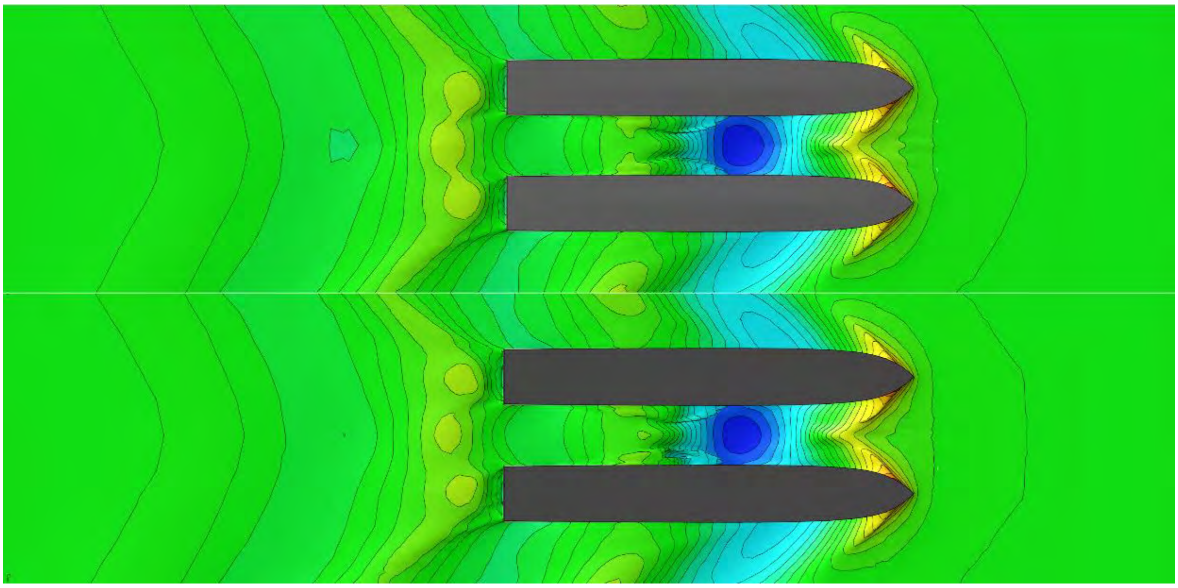
Furthermore, for a catamaran the flow between the demi-hulls can be of high importance due to the interactions of the waves and the stability and steadiness of the flow, particularly for closely positioned demi-hulls at higher Froude numbers. Hence, the baseline was analyzed both with a mirror plane boundary condition and as a full model with the two demi-hulls in place. This was done to evaluate the validity of utilizing mid-ship symmetry – which of course is favored due to being twice as fast. Fig.9 (B) depicts the free surface for both set-ups, using the coarse mesh: The mirror plane is nicely visible since the flow is not perfectly continuous while the full model features a minor asymmetry. Nevertheless, the two wave patterns match very well, the difference in total resistance being 2 N and, hence, negligible.

Consequently, it was decided that a mirror plane simulation on the coarser mesh with 500 000 cells would be sufficient to capture all of the important flow patterns and to get reliable resistance values. This can be considered a “competitive” numerical set-up that should allow for many design variations in a short timeframe, even on local workstations, fairly balancing speed and accuracy.

The total resistance values computed for the baseline are shown in Fig.10. At 7 kn the resistance is more than ten times the one at 3.5 kn, for both loading conditions. And there is an almost 50% resistance increase from the empty ferry with just the crew on board to the ferry fully-loaded with passengers. From the operating profile it is estimated that for around 50% of the time the cat would sail at maximum speed of 7 kn, independent of the loading condition. Hence, higher speed at both drafts clearly dominate the overall power consumption so that they were selected as the relevant operating points for which to optimize. It should be kept in mind that no information at 3.5 kn would be known to the optimizer and that the energy consumption when maneuvering in port or when accelerating to top speed are also left out of the investigation. However, when looking at the prominent resistance values at design speed these simplifications should still yield reasonable results, providing designs with decreased battery consumption, in particular when recalling that the campaign is run at the tender stage.



(A) Influence of mesh density on free surface elevation
(top: fine mesh with 1.1 million cells, bottom: coarse mesh, 500 000 cells)



(B) Effect of utilizing a symmetry plane
(top: half model simulation, using a mirror plane, bottom: full model with both demi-hulls)

Fig.9: Initial investigation of mesh density and symmetry plane

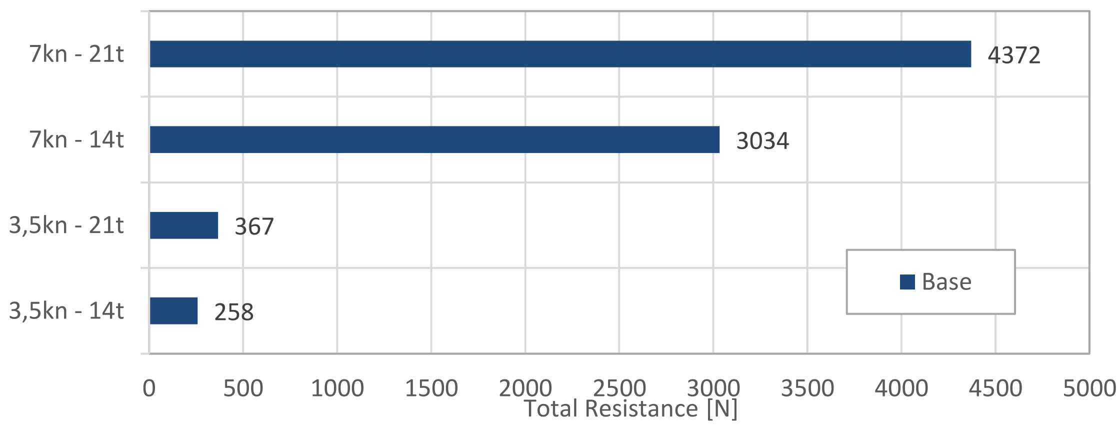
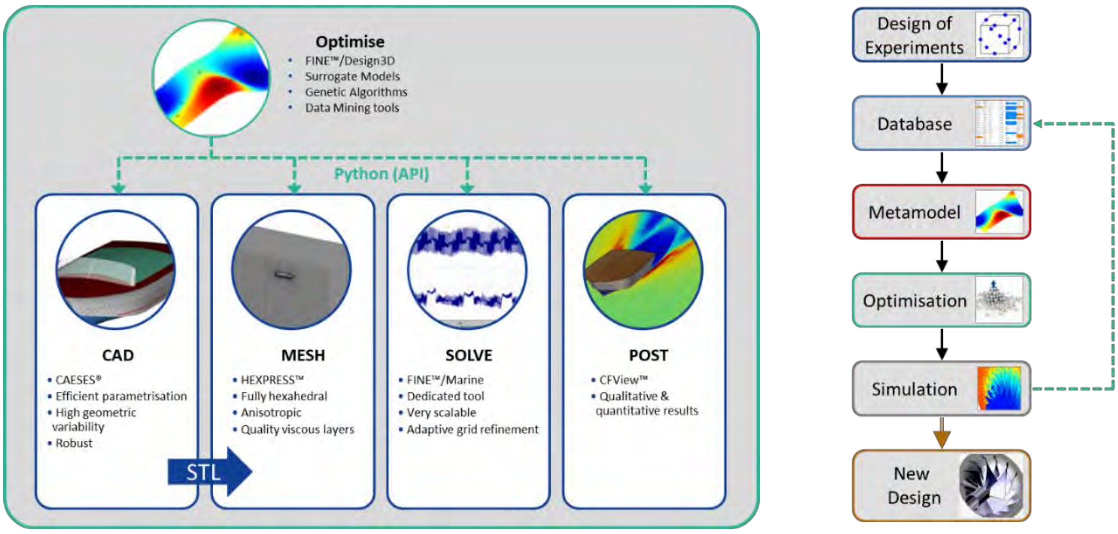


Fig.10: Total resistance for the baseline (Base), using the CFD set-up for the optimization

5. Optimization campaign

5.1. Overview

Next step was the assembly of the optimization chain as illustrated in Fig.11 (A). The optimization tool employed was NUMECA FINE™/Design3D, which controls all the sub-processes like geometry variation and export, meshing, solver runs and data collection in the post-processor. A Python API ensures a flexible and easy to use access to the various tools and exchange of data.



(A) Optimization chain from CAD to post-processing

(B) Surrogate based optimization loop

Fig.11: Optimization chain and loop

The optimization loop itself is based on a surrogate model, here radial basis functions. (It is worthwhile to note that RBF cannot only be used for geometric variation as discussed above but also as a response surface technique.) The approach is shown in Fig.11 (B). It starts with the generation of a database which stems from a sampling of the design space via a Design-of-Experiment (DoE). It aims at a maximum scattering of the samples within the bounds of the free variables with as few designs as possible. Here, 10 free variables were used which span a 10-dimensional design space, see Table III and Fig.8.

From this discrete set of data points, bringing together geometry and performance, a surrogate model is built which offers a continuous description that is cheap and fast to evaluate. An evolutionary algorithm then calls this surrogate model thousands of times to generate new candidates in the design loop. The algorithm mimics evolutionary processes with selection of strong traits in a design with respect to the performance and to the constraints over several generations. Weak samples tend to become extinguished while methods like mutation help to keep a large diversity from one population to the next. In the end such an optimizer yields a high probability of finding optimum solutions, even globally, especially in comparison to local strategies such as a gradient method. Since the actual search is performed on the surrogate model the number of variants can be very high without using any tangible computer resources. When a new and promising candidate is identified it is evaluated by means of (substantially more expensive) CFD simulations, using the optimization chain. The results are subsequently appended to enrich the database and to provide an even better surrogate model. The process is then re-started until convergence.

5.2. Design-of-Experiment

Prior to starting the DoE to create the actual database a few checks for plausibility of parameter ranges and stability of the meshing and workflow templates were made. Naturally, the bounds of the free variables constitute a crucial input to any optimization: It is desirable to have sufficient geometric variability while as few variants as possible should be unusable. The latter can appear quite easily if the chosen parametrization is not well-suited for the design task or if extreme parameter combinations lead to designs that any engineer would readily reject. Moreover, any failure in the optimization chain should be handled correctly by the optimizer. Machine issues or plain technical issues like licensing must be identified so that the optimizer does not neglect any region in the design space which could be of interest. In addition, physical phenomena like excessive drag or strong unsteadiness in resistance values should also be monitored. As mentioned above the time series for total resistance for each variant was evaluated for the last 30% of simulation time, delivering both a mean value as objective and a standard deviation for quality checks.

Results of the DoE, i.e., the database run, are displayed in Fig.12, giving the mean total resistance values for both operating points. The baseline is shown in the center, indicated via a large blue cross, while the points give the performance of the 20 DoE-samples. There is a strong correlation between the two different drafts, although outliers do exist. The overall scattering of the resistance is quite large, and there is only little clustering of the designs, which indicate a nice sampling even with as low as 21 variants in total. As can be seen there are variants that perform far worse but also quite a bit better. An impressive resistance reduction by 25% and 39%, respectively, is (happily) found for the best sample.

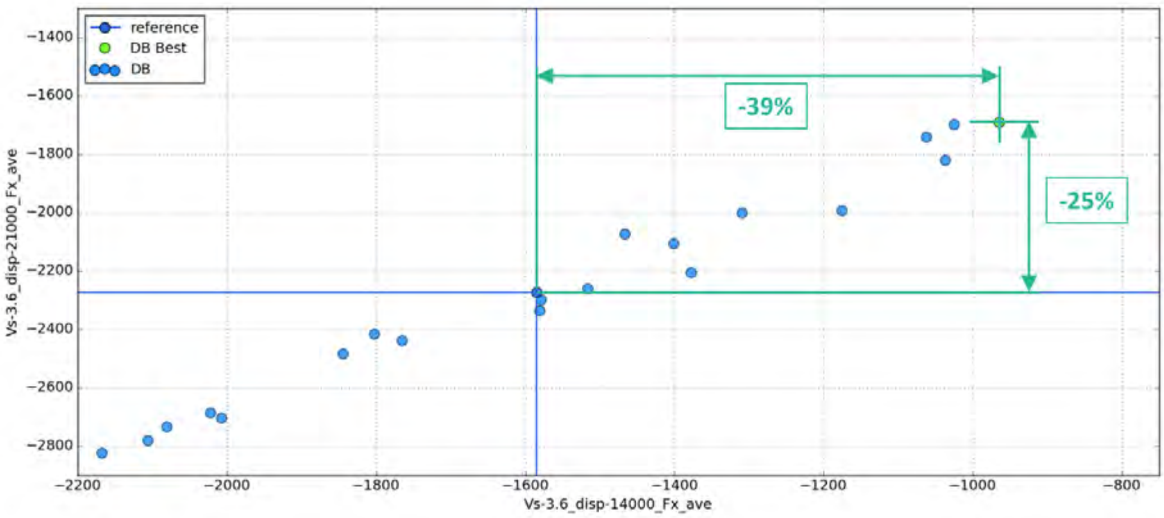


Fig.12: Total resistance values for the database samples for 7 kn at 14 t and 21 t

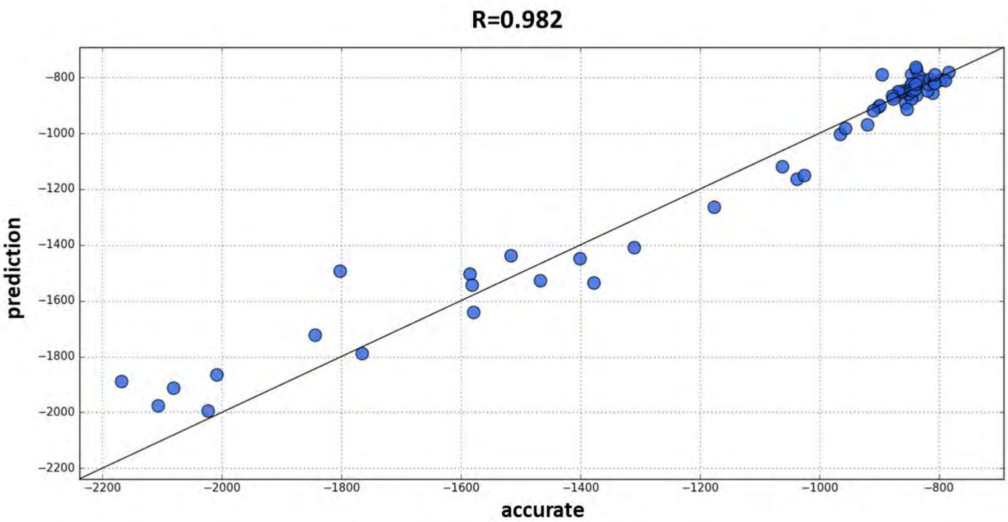


Fig.13: Correlation between surrogate model prediction and CFD values for 7 kn at 14 t

A surrogate-based optimization relies heavily on the quality of the prediction. If a surrogate model does not predict new and unknown variants with a certain accuracy or even fails to capture trends correctly there is no chance for any optimizer to find good solutions, at least within a reasonable timeframe. One way to quantify the accuracy is the so-called leave-one-out analysis, which calculates the correlation and, hence, the surrogate quality of a given set of data without the need for an additional set of evaluation samples. Such an analysis is depicted in Fig.13. It gives the total resistance values for 7 kn at 14 t from both the flow solver (accurate) and the surrogate (prediction). The samples line up quite nicely, i.e., they are near to the ideal linear correlation, and the R value 0.982 is close to one.

5.3. Multi-objective optimization

As said the resistance values for design speed at both drafts were chosen as the optimization objectives. After a more detailed check of the database it was not deemed necessary to use any constraints or further objectives here. A possible candidate for an inequality constraint could have been the trim angle which should not reach excessive values in order to maintain passenger comfort. But all variants in the DoE were well-behaved and the focus could be put on resistance. Thus, the final optimization turned out to be unconstrained and multi-objective. A strength-based Pareto formulation was employed, *Zitzler et al. (2001)*, which tends to deliver a selection of good designs which still show diversity, i.e., they do not cluster in one region of the design space. This is true especially for very complex problems with many parameters, constraints and objectives. Towards the end of such an optimization a clear Pareto frontier should form, which collects the variants that cannot be further improved in terms of one objective without impairing any other objective. It is then up to the design team to select the best solution from these non-dominated variants by identifying the best trade-off between competing objectives.

Results from the optimizer run are given in Fig.14. The best variant from the DoE is given in green. It can be regarded as the new reference point to beat. All promising optimizer variants – double-checked with CFD – are given as orange dots. Interestingly, none of these new designs performs worse than the reference point with regard to resistance at 14 t. This indicates again the validity of the surrogate model which was utilized to produce the improved variants. Due to the short timeframe of the project – and the need to freeze the lines – it was decided to stop the process at this point. The Pareto set, here the designs in the upper right region of Fig.14, is made up of only a handful of variants which suggests that there might be even more room for improvement. Still, another large reduction in total resistance could be achieved. Altogether, the new design reduces power consumption by 40% at fully-loaded conditions and by 47% at reduced draft when compared to the baseline.

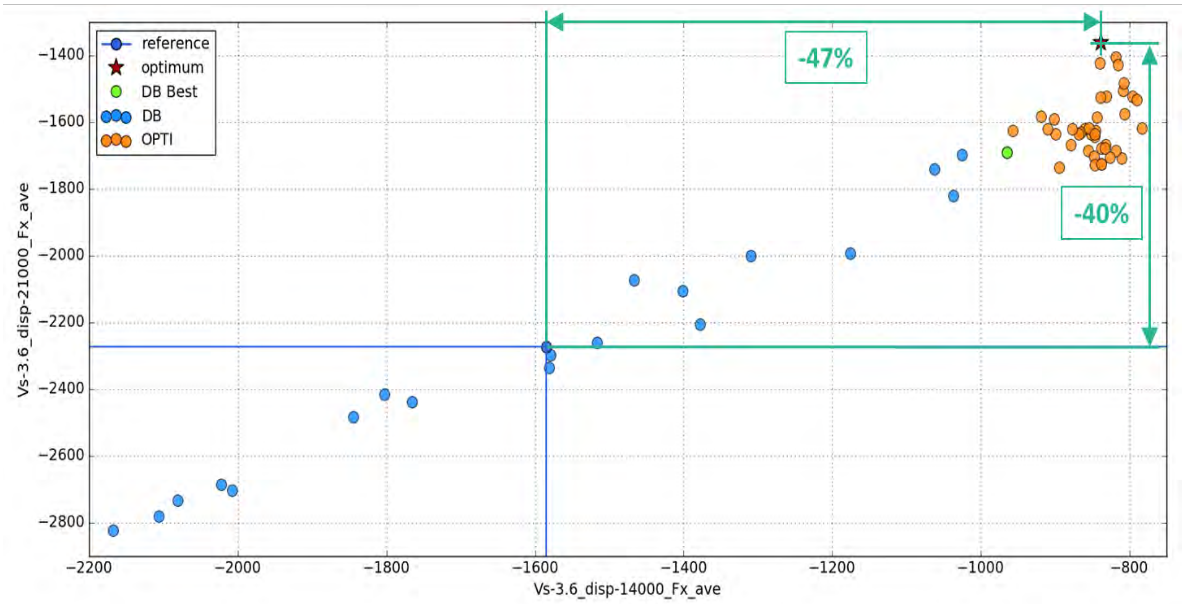


Fig.14: Total resistance values for the optimizer samples for 7 kn at 14 t and 21 t

5.4. Quality checks

To validate results and gains in the optimization, a final set of CFD runs was performed. Both hulls were used (no mirror plane), and the mesh density was increased to five million cells. The AGR thresholds were adjusted so that around 200 000 cells were created additionally just for accurate wave capturing. Furthermore, the mesh was refined to apply a low Reynolds wall model for turbulence. An additional displacement of 17.5 t was also studied to understand the influence on an intermediate draft.

Results for these simulations for both the baseline and the optimized hull are summarized in Fig.15. The trends are not only fully kept but the absolute gains are (by chance) even slightly higher on this refined CFD set-up. Also, at 17.5 t the performance is substantially improved, too, as was anticipated. At the low speeds no improvements are found and there is even a slight increase of total resistance at 21 t. It should be kept in mind that these operating points were deliberately left out of the optimization, primarily for reasons of speeding up the process, so that these results do not come as a surprise. As can be appreciated from the comparison between the baseline and the optimized hull the energy-efficiency of the cat has been improved considerably.

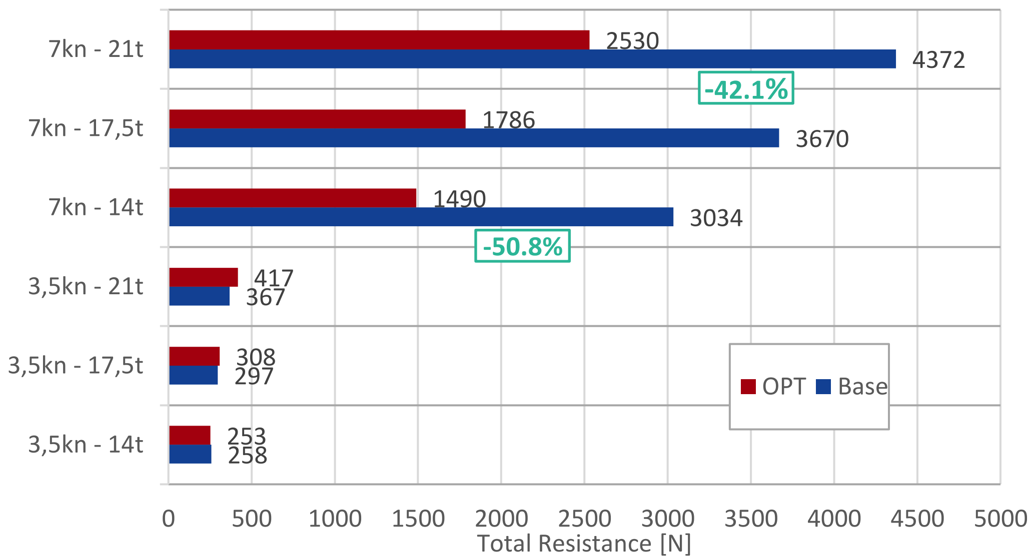
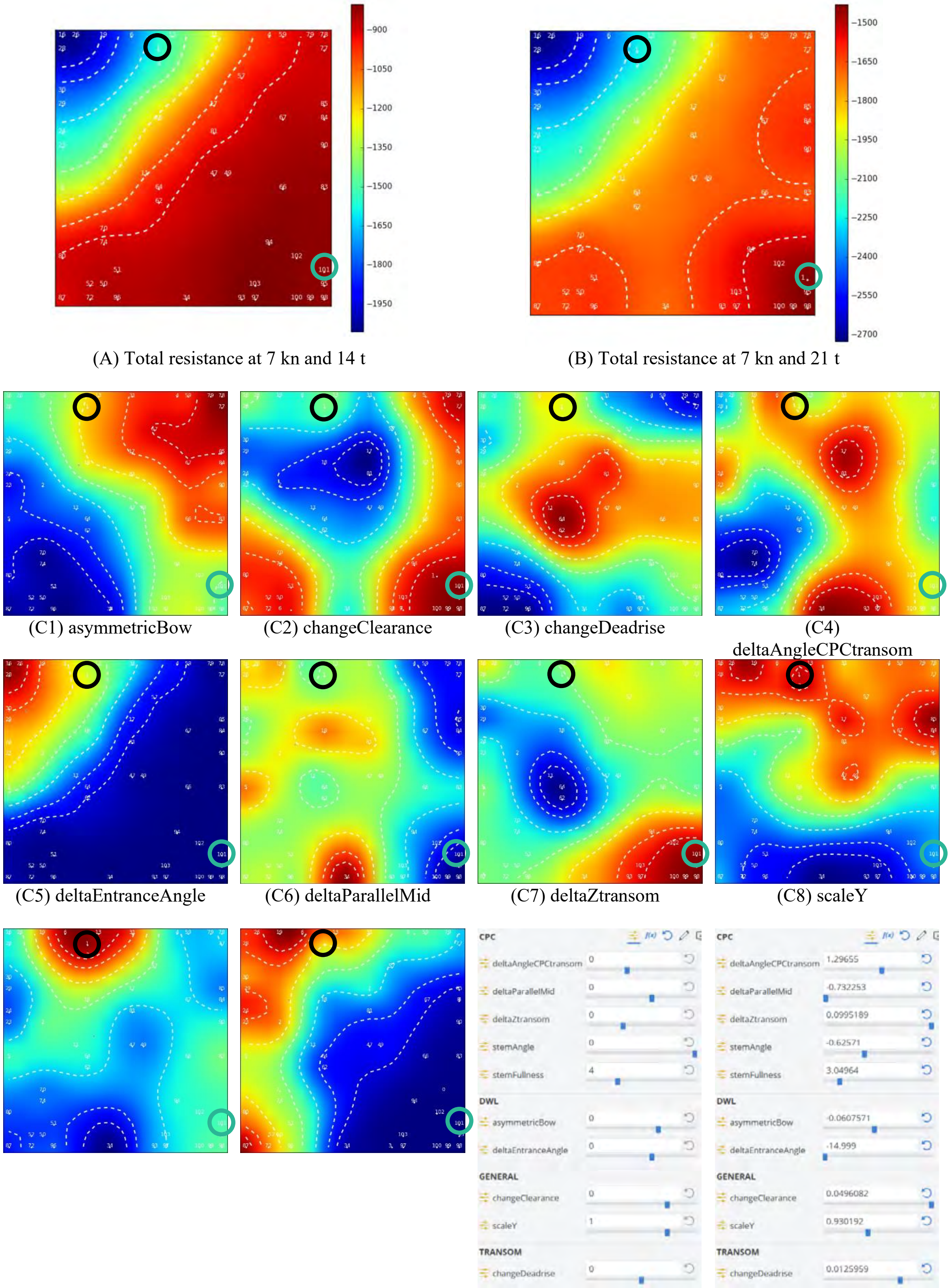


Fig.15: Comparison of design performance of the baseline (Base) and the optimized hull (OPT)

5.5. Data mining

Optimization projects create a vast amount of data, lots of geometries are generated and simulated on various operating points. This is indeed a treasure box of information – but one that is not easily accessible to the designer. Data mining intends to provide tools to display these treasures in an easy-to-use and intuitive way.

One such tool is the Self-Organizing Map (SOM). Here, high-dimensional data is projected into two-dimensional space, using an artificial neural network and fixing the location of each data point (which equals a given design). This allows a systematic comparison and correlation of data. The SOMs for the objectives and the input parameters are given in Fig.16. For example, one can see from the two top plots, Fig.16 (A) and (B), that there exists a strong correlation between the performance at both drafts, with the worst scenario in the top left corner and the best scenario in the lower right corner. In between there are zones where the correlation is not perfect, though. The black circles mark the location of the baseline (see also Fig.8 (A)) and the green circles indicate the optimized hull (see also Fig.8 (B)). From a performance point of view, the new design features the lowest resistance at 21 t out of all variants, while still being very good at 14 t. However, if the lower draft condition was the main operating point of interest other samples, e.g. variant 93, would be more favorable.



(A) Total resistance at 7 kn and 14 t

(B) Total resistance at 7 kn and 21 t

(C1) asymmetricBow

(C2) changeClearance

(C3) changeDeadrise

(C4) deltaAngleCPCtransom

(C5) deltaEntranceAngle

(C6) deltaParallelMid

(C7) deltaZtransom

(C8) scaleY

(C9) stemAngle

(C10) stemFullness

(D) Values of free variables for the baseline

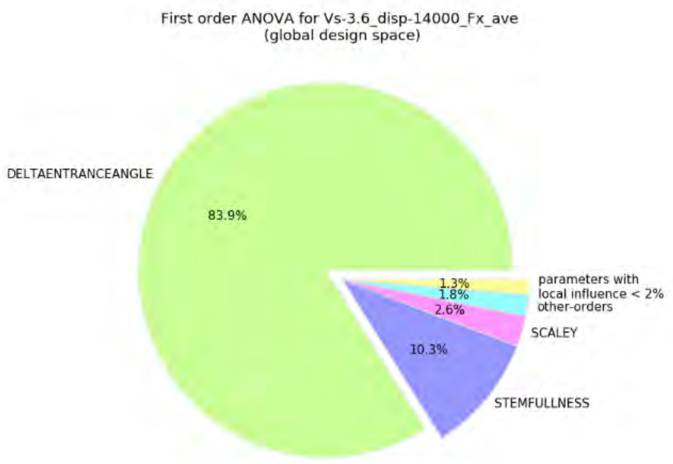
(E) Values of free variables for the optimized hull

Fig.16: SOMs for the objectives (total resistance) and the ten free variables

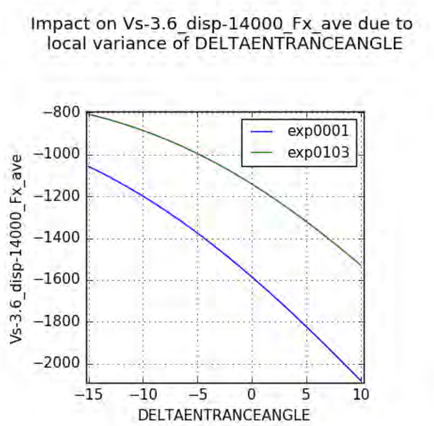
There exists an obvious correlation between resistance and some of the free variables, especially the free variable called deltaEntranceAngle (see Fig.6 (A) and (B)): A more slender bow has a very positive effect. Also, the stemFullness (see Fig.6 (E) and (F)) correlates quite well with resistance values. Some of the other free variables display some more complex correlations, e.g. changeClearance or deltaAngleCPCtransom. When aiming for an ideal hull for light loading conditions, these parameters would be rather sensitive.

Analyzing such data can clearly help a designer to find trends and connect specific geometric variations to their effect on any quantity of interest. Re-using such knowledge in further optimization runs or, possibly, in new projects then helps to design even better hulls from the outset or improve the total turnaround time by focusing on the most important geometrical features.

An additional tool for data mining is the analysis of variance (ANOVA). It calculates the global sensitivities of each response like objectives and constraints with regard to the input parameters. Fig.17 (A) shows such an ANOVA for the results at 7 kn and 14 t. It can be clearly seen that the most important free variable is the deltaEntranceAngle, which controls the slenderness of the bow around the design waterline. Second comes the stemFullness. These two free variables were also found to be correlating strongly from the SOM plots. For each parameter a local variation can be plotted, see Fig.17 (B). This gives the variation of an output with the change of the parameter for a given design, here the baseline and the optimized one. These tools again allow the development of a deeper understanding of the importance of a given geometric variability. For the cat optimization one could now refine the parametrization of the bow region by using more parameters for finer control so as to improve the optimization results even more. Alternatively, some parameters of low importance could be removed, for instance when doing further optimizations. It can also help to save resources in a comparable project for a similar hull.



(A) Parameter sensitivity on total resistance



(B) Impact of local variance for deltaEntranceAngle

Fig.17: ANOVA for 7 kn at 14 t

6. Selected results

6.1. Comparison of designs

Fig.8 shows the baseline and the optimized hull, Fig.18 the wave patterns of both designs. These results are obtained using the refined CFD set-up for quality checks as described in section 5.4. An important difference is the decrease in the bow wave system and a less pronounced trough in the tunnel. The stern wave system on the other hand seems quite a bit stronger for the optimized hull.

Nevertheless, the resulting waves far from the hull are reduced for the optimized hull, having a positive effect on total resistance. Moreover, the influence of the slight asymmetry of the bow on the flow can be seen, too. In an unsteady evaluation also an unstable flow pattern can be observed between the demi-hulls of the baseline. This is does not show at all for the optimized hull.

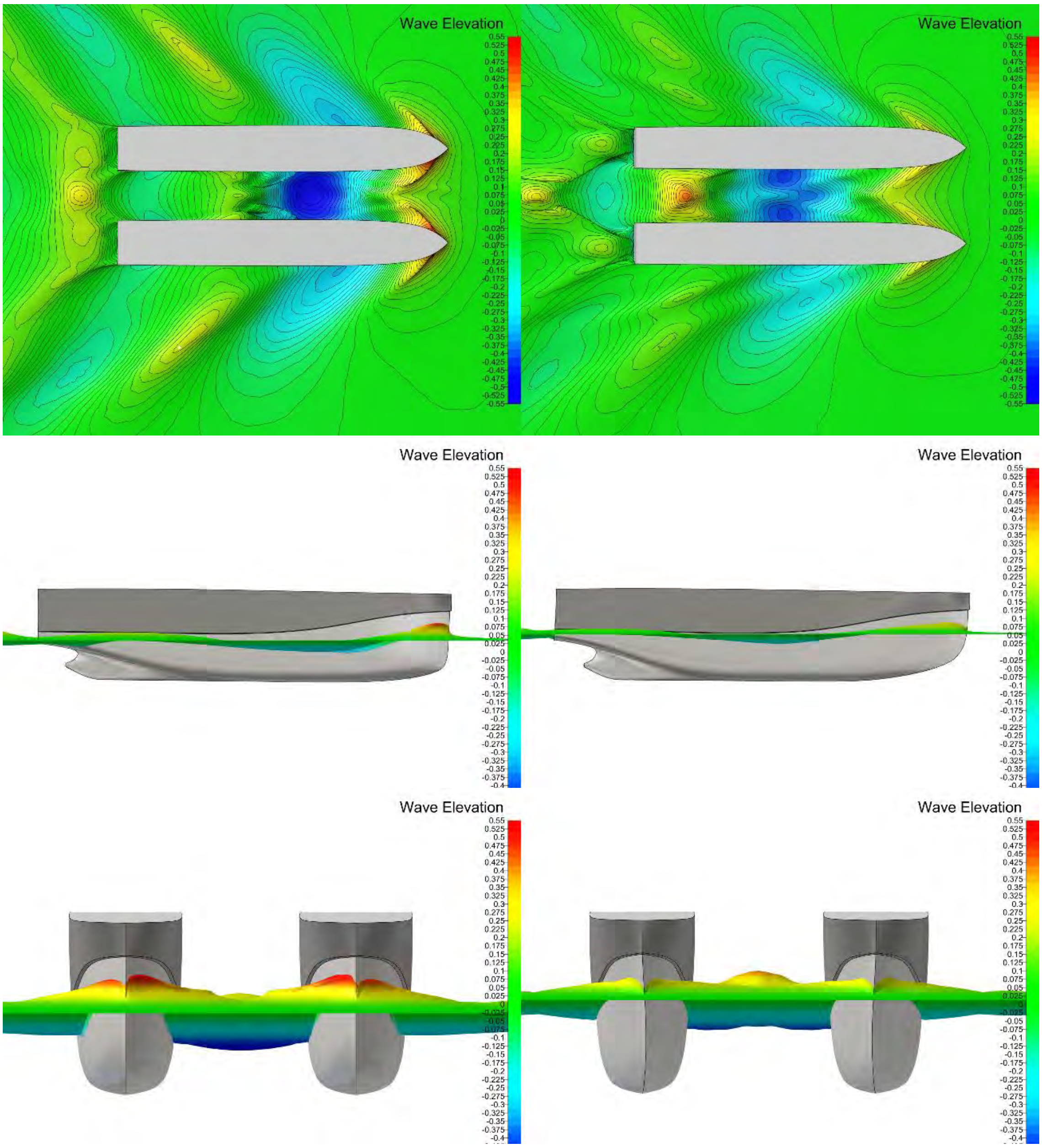


Fig.18: Comparison of wave patterns; baseline (left), optimized (right)

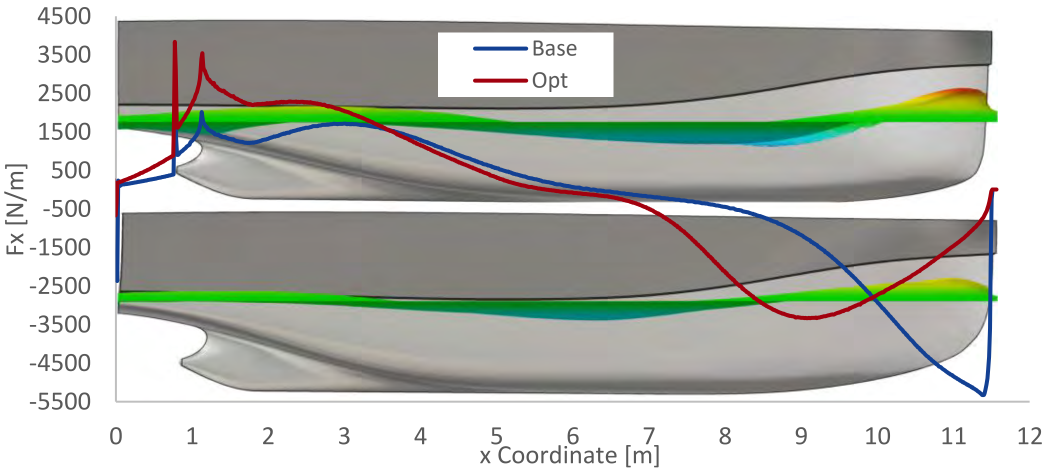


Fig 19: Wave profile and sectional forces along the hull: stern at 0, bow at 11.5 m
(upper part: baseline (Base); lower part: optimized hull (Opt))

A more detailed insight into the force distributions along the hulls is depicted in Fig.19, giving sectional forces along with the wave profile. The stern is located at x = 0 m and the bow at 11.5 m. The smoother bow wave in the optimized hull can be seen clearly. The bow drag is shifted downstream and, in general, the sectional forces are lower for the forebody of the optimized hull. Major gains are observed in the aftbody, however, pushing the hull and thereby reducing the total resistance.

6.2. Resources spent

The total resources spent can be taken from Table IV. Clearly, the entire project was carried out within a very tight timeframe. Besides showing tangible potential gains already at the tender stage it also showcases what can be achieved when coupling expertise and modern engineering software.

Table IV: Resources spent

Partner	Description	Resources
Yachtwerft Meyer	Design of the baseline	2 to 3 days
FRIENDSHIP SYSTEMS	Set up and fine-tune RBF	1 day
FRIENDSHIP SYSTEMS	Develop parametric skeg model	1 day
NUMECA Ingenieurbüro	Check CFD and ensure quality	1 day
NUMECA Ingenieurbüro	Streamline process	1 day
NUMECA Ingenieurbüro	Number crunch CFD and run optimization	3 nights
All	Meet and discuss project and results	Several 1-h virtual meetings

7. Conclusions

The paper presented a project for the parametric modeling and hydrodynamic optimization of a small electric catamaran ferry at the tender stage. The parametric modeling was based on RBFs which enable a rather intuitive set-up for shape variations. The hydrodynamic optimization campaign was built on a high-fidelity free-surface RANS solver with free sinkage and trim. The project illustrates what can be achieved by suitably combining expert knowledge from different fields quickly and without any overhead, using the experience from a yard (here Yachtwerft Meyer), the know-how from a software developer with specialization in variable geometry (here FRIENDSHIP SYSTEMS) and the expertise from a software provider with focus on high-end simulations (here NUMECA Ingenieurbüro). Tangible improvements for the design could be found within just a few days of actual work, a few nights of number crunching and a handful of virtual meetings. It is hoped this serves to encourage to undertake simulation-driven design also for smaller craft at a wider scope.

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Predictive Motion Control of High-Speed Vessels

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Abstract

In this paper we demonstrate how big data and state of the art machine learning techniques are used to build, test and deploy intelligent models to predict and optimize motion of High Speed Craft (HSC). We show that the motion performance can be improved by using machine learning models to predict vessel response and optimise controller settings on-board based on encountering Metocean conditions. It is also shown that the deployed prediction-optimisation controller has the potential to reduce roll RMS by up to ~25% and MSI by up to ~15%. Finally, we show how a system based on one of these strategies is deployed in the real-world.

1. Introduction

To maximise comfort and minimise sickness in harsh wave environments, it is important to control vessel motion. The objective of the vessel Motion Control System (MCS) is to ensure that the vessel follows a desired response. The desired response can be for the vessel to follow a defined path by controlling low frequency motion and/or avoiding large undesired motion (in particularly roll motion) by controlling wave frequency motion.

The desired vessel response is achieved using force generation devices. These can be passive or active, and several solutions such as bilge keels, gyroscopic stabilizers, anti-rolling tanks, active lift surfaces and rudder roll stabilization have been proposed and implemented on different ship types. Among these, the active lift surfaces solution is the most popular device type for HSC. The development of control algorithms for lift surfaces is an active research field and several control algorithms, such as ones based on the classic PID control strategy, have been developed to improve motion during operations.

A key problem in ship motion control is the effect of environmental disturbances, such as waves, winds and water currents, and how these influence the stability of the vessel and induce undesirable motion. An ideal controller needs to estimate these disturbances in advance and adjust the parameters accordingly to maintain the required motion criteria.

Recent advancements in Big Data Analytics, Artificial Intelligence (AI) and computing power bring new opportunities for ship motion control. This can include reducing the impact of changing external environmental conditions to ship response by adjusting the control system's command. Different AI based strategies can be used to utilise data gathered on-board of the vessels and use them to either tune controller parameters online or directly learn the optimum control strategy to achieve desired objectives. The use of AI for ship motion control has recently attracted attention. *Liu et al. (2017)* used a Genetic Algorithm to tune the parameters of a PID controller in dynamic positioning. *Larrazabal and Penas (2016)* combined GA with PID for trajectory control of an unmanned marine surface vessel (USV). They used a scaled model to derive the system dynamics model for the USV and used that in the trajectory estimation of the vessel. *Ahmed (2012), Ahmed and Hasegawa (2013)* used Artificial Neural Network (ANN) for automatic ship berthing. They used a combination of different ANNs for command rudder angle and propeller revolution output during berthing. For a comprehensive review of state-of-the-art researches on motion control of ships the readers are referred to *Wang et al. (2019).*

In this paper, deep learning is used to find the model of ship response to external disturbances and control surfaces based on the data gathered during operations. The model is then used along with a Genetic Algorithm and model of the nonlinear controller function to improve vessel motion as an advisory system for the crew, making recommendations to adjust the controller parameters based on the conditions.

2. Background

Here, we briefly provide some background on system dynamics, which comprise the vessel, control surfaces and controller, and then introduce the different control strategies used in this paper.

2.1. System dynamics

The aim is to control ship motion in given modes of motion by adjusting the control surface angle of attack. The Cummins equation, *Cummins (1962), Ogilvie (1964),* is used to model vessel hydro-dynamics and takes the form:

$$\left(\underline{\underline{\boldsymbol{M}}} + \underline{\underline{\boldsymbol{A}}}^{\infty}\right) \cdot \ddot{\underline{\boldsymbol{\xi}}}(t) + \int_0^t \underline{\underline{\boldsymbol{K}}}(t-\tau) \cdot \dot{\underline{\boldsymbol{\xi}}}(t) d\tau + \underline{\underline{\boldsymbol{G}}} \cdot \underline{\boldsymbol{\xi}}(t) = \underline{\boldsymbol{F}}^{wave}(t) + \underline{\boldsymbol{F}}^{controller}(t) \tag{1}$$

$\boldsymbol{\xi}(t)$ is the displacement vector of the centre of gravity, $\boldsymbol{M}$, $\boldsymbol{A}^{\infty}$ and $\boldsymbol{G}$ are the mass, infinity added mass and hydrostatic stiffness matrices, $\boldsymbol{F}^{wave}(t)$, $\boldsymbol{F}^{controller}(t)$ are the wave excitation and controller forces and $\dot{\xi}(t)$ and $\ddot{\xi}(t)$ represent first and second time derivatives of displacement vector (i.e. velocity and acceleration).

The motion control strategies explored here are based on active control surfaces. Assuming a control surface at a position $\bar{\boldsymbol{r}}^f = (x^f, y^f, z^f)$ relative to the vessel centre of gravity and with a given angle θ with respect to horizon, the control surface force on the ship (the controller force) takes the form:

$$\underline{\boldsymbol{F}}^{controller}(t) = \begin{bmatrix} 0.0 \\ F_{lift}(t) \cdot \sin\theta \\ F_{lift}(t) \cdot \cos\theta \\ F_{lift}(t) \cdot y^f \cdot \cos\theta - F_{lift}(t) \cdot z^f \cdot \sin\theta \\ -F_{lift}(t) \cdot x^f \cdot \cos\theta \\ F_{lift}(t) \cdot x^f \cdot \sin\theta \end{bmatrix} \tag{2}$$

where

$$F_{lift}(t) = \frac{1}{2}\rho \frac{\mathrm{d}C_L}{\mathrm{d}\delta} A^f U^2 \delta_e(t)$$

$$\frac{\mathrm{d}C_L}{\mathrm{d}\delta} = 2\pi \frac{\Lambda(\Lambda+1)}{(\Lambda+2)^2} \tag{3}$$

$\Lambda = s^2/A$ is the control surface aspect ratio. Here, the lift coefficient is presented using Söding′s formulation, *Söding (1984),* and for more details the readers are referred to *Faltinsen (2005).*

The effective angle of attack is calculated as

$$\delta_e(t) = \arctan\left(\frac{\dot{z}(t)\cos\theta + \dot{y}(t)\sin\theta}{U}\right) + \delta(t) \tag{4}$$

$\dot{y}$ and $\dot{z}$ are the horizontal and vertical velocities of the control surface relative to the water and take the form

$$\begin{aligned} \dot{y}(t) &= v(t) - \dot{\xi}_2(t) + z^f \dot{\xi}_4(t) - x^f \dot{\xi}_6(t) - U\xi_6(t) \\ \dot{z}(t) &= w(t) - \dot{\xi}_3(t) + x^f \dot{\xi}_5(t) - y^f \dot{\xi}_4(t) + U\xi_5(t) \end{aligned} \tag{5}$$

$v(t)$ and $w(t)$ are the horizontal and vertical wave particle velocities at the location of the control surface. The effective angle of attack to the surface is controlled by adjusting the flap angle. In this paper, a control law in the form of:

$$\delta(t) = \mathcal{F}^{nl}\left(\xi_4(t), \xi_5(t), \dot{\xi}_4(t), \dot{\xi}_5(t), K_i\right) \quad i \in [1, \ldots, 6] \tag{6}$$

is used to control the angle of attack. Here, $[K_1, \cdots, K_6]$ are constant coefficients and should be adjusted based on vessel speed, loading and wave conditions (height, period and direction with respect to vessel heading) to achieve an efficient control strategy. Furthermore, $F^{nl}(x)$ represents a nonlinear function of input variable x.

2.2. Motion Sickness

There are several quantitative indices to measure motion sickness induced by whole-body vibration in the low-frequency range. Motion Sickness Dose Value (MSDV) is a recognised index and is referenced by multiple international standards, such as BS 6841 and ISO 2631-1, *ISO (1997)*. MSDV is defined as

$$MSDV = \sqrt{\int_0^T a_{wf}^2(t)dt} \tag{7}$$

a_{wf} is the frequency weighted root mean square (RMS) of vertical acceleration, *Lawther (1988),* showed that this MSDV is linearly related to the vomiting incidence, and also to the various level of the illness ratings. This led to the following equation

$$MSI = k_m \cdot MSDV \tag{8}$$

where $k_m = 0.33$ is a good estimation for the percentage of people who are expected to vomit for a particular MSDV.

2.3. Ship

The results described in this paper are for an Austal built high-speed catamaran. Table I shows the general information of the vessel.

Table I: High speed craft characteristics

Hull form	Length	Beam	Speed
Catamaran	115 m	26 m	34 kn

In order to control the roll and pitch motions, the vessel is equipped with interceptors and T-foils. The command to these surfaces are then estimated using Austal's non-linear motion control law, Eq.(6).

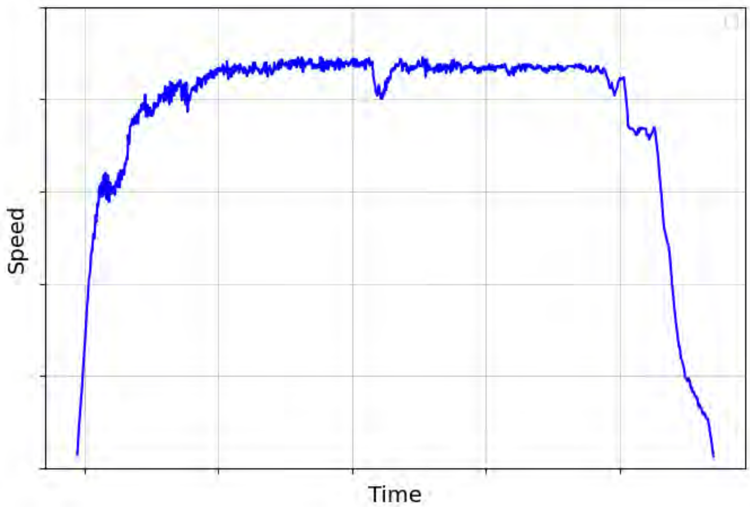


Fig.1: Speed over Ground profile

3. Prediction of motion metrics

In order to build predictive models each journey was decomposed to segments of 10 minutes length. The duration of the segments was selected to ensure sufficient time to capture the influence of variations in parameters, whilst still being short enough to avoid strong smearing of these variations. As shown in Fig.1, the vessel speed profile consists of three main sections, a ramp up zone when the vessel starts the journey and leaves port, a semi-constant zone when the vessel is cruising in open water and finally a ramp down zone as the vessel approaches the destination. To build the predictive models the ramp up and ramp down sections were removed from the data. Only the data during the cruising section where the vessel is travelling with semi-constant speed were considered.

3.1. Data acquisition

In order to build the motion prediction models, the vessels were equipped with Inertial Measurement Units (IMU) sampling linear acceleration and rotational velocities at 5 Hz. In addition, vessel displacement and trim were calculated using ultrasound readings at forward and aft of the vessel. The data were then combined with GPS readings to provide vessel speed over ground, location and calculated Met-ocean conditions from an external source API, https://www.tidetech.org. Table II shows the summary of the gathered data, the Metocean data are requested every 10 min from external source API. Data is gathered automatically on-board of the vessel, time-stamped and transferred for storage in Austal's secure cloud-hosted storage service.

Table II On-board gathered data

Data	Frequency	Description
IMU	5 Hz	Linear acceleration and rotational velocities
SoG	1 Hz	Speed over Ground
Motion Control surfaces	1 Hz	Command/feedback to the control surfaces
Motion Control settings	1 Hz	Controller coefficients (see Eq.(6))
Ultrasounds	1 Hz	Distance to water surface at front and aft of the vessel
GPS	1 Hz	Latitude, longitude and heading of the vessel
Metocean		Wave, wind and current conditions from external source

3.2. Data Preparation

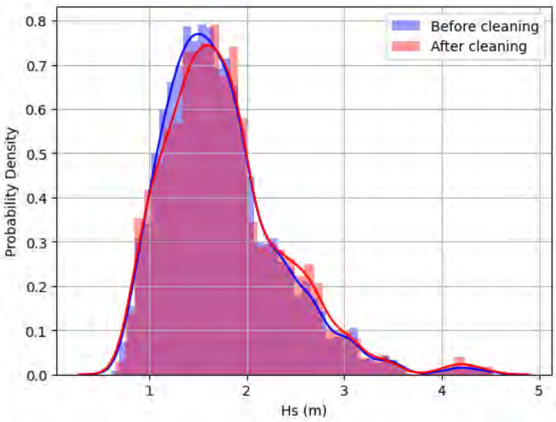
Prior to build any predictive models it is necessary to clean the data and remove anomalies. This is done through the following steps:

1. The periods with missing data were removed from the datasets. It is possible to fill the gaps in data by interpolation, but this would result in introducing errors in the final models.
2. The isolation forest, *Liu et al. (2008)*, was used for anomaly detection and removals. The isolation forest efficiently uses random forests to perform outlier detection in high-dimensions and in unsupervised manner. Here, Scikit learn package, *Pedregosa et al. (2011),* is used for isolation forest anomaly detection.

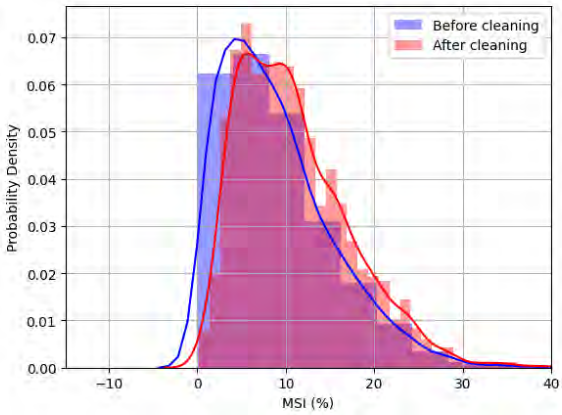
Finally, the vessel-wave encounter frequency was calculated for every segment and added to data columns. The vessel-wave encounter frequency is calculated as:

$$\omega_e = \left(\omega + \omega^2 \frac{V}{g} \cos\beta\right) \tag{9}$$

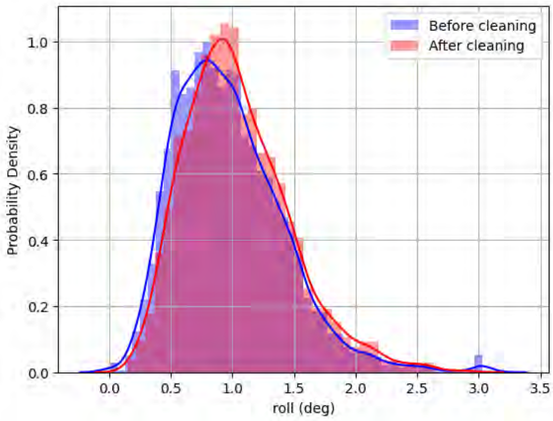
ω is the wave frequency, V is the vessel speed and β is the relative angle between mean wave direction and vessel heading ($\beta = 0$ represents head sea).



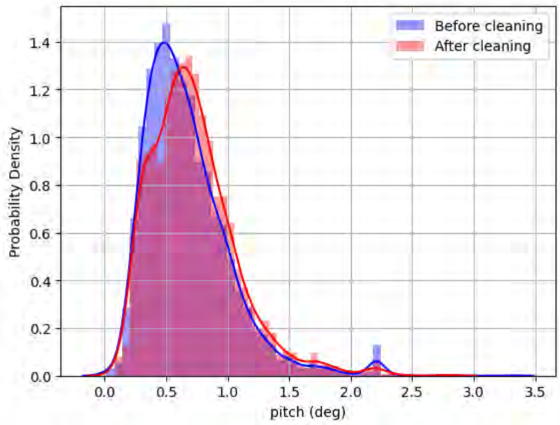
(a) Significant Wave Height



(b) MSI



(c) Roll RMS

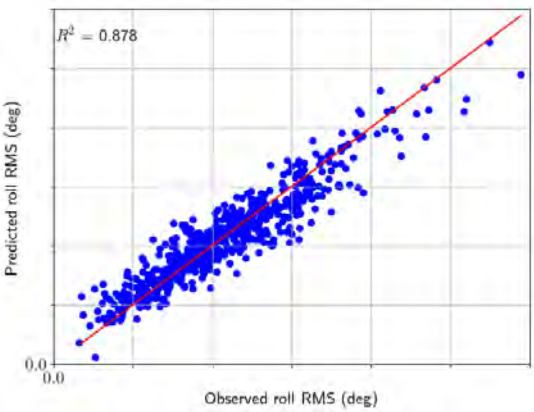


(d) Pitch RMS

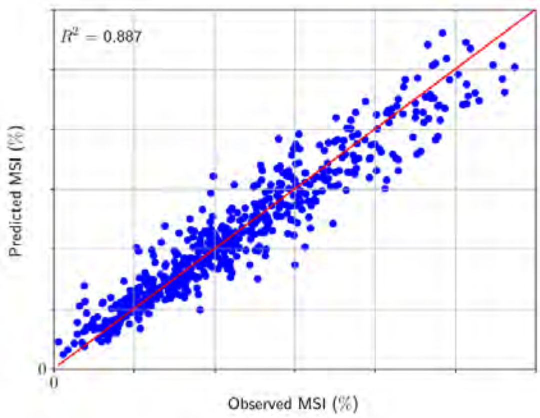
Fig.1: Distributions of data before and after cleaning

3.1. Prediction

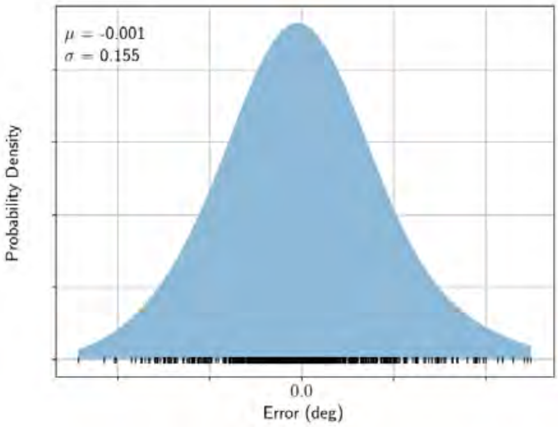
The data were gathered for ~1000 operational hours and a Neural Network model was fitted to the dataset to predict the motion metrics based on the loading and environmental conditions. The PyTorch library, *Paszke (2019),* was used for the Neural Network model and the Optuna package, *Akiba (2019),* was used for hyper-parameter optimization of the network. Fig.2 shows the prediction accuracy of the model for roll RMS and Motion Sickness Incident (MSI) over the test dataset.

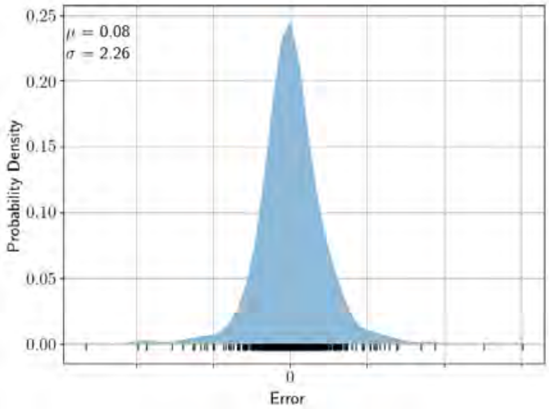


(a) roll RMS



(b) MSI





(c) error distribution for roll RMS (d) error distribution for roll MSI

Fig.2: Prediction accuracy of Neural Network model for roll RMS and MSI against measurements

3.2. Optimisation

Fig.3 shows the schematics of the predictive controller. The system can be considered as a slow dynamics Model Predictive Controller as the deployed predictive controller is based on predicting the RMS of motion as a function of the controller coefficients, Metocean conditions, vessel loading and vessel speed. It then uses an on-board online optimisation algorithm based on Genetic algorithm to find the optimum controller coefficients to minimise the predicted motion metrics, which are then communicated to the crew. GA is a heuristic search and optimisation algorithm inspired by Darwin's natural evolution concept, *Holland (1975)*. In summary, GA starts with a random population of candidate solutions and through various operators and iterations they are evolved toward the global optimum of the objective function (which is called fitness function in GA literature). Here, the PYMOO library, *Blank (2020),* with costumed crossover and mutation functions have been used for optimisation of the controller coefficients.

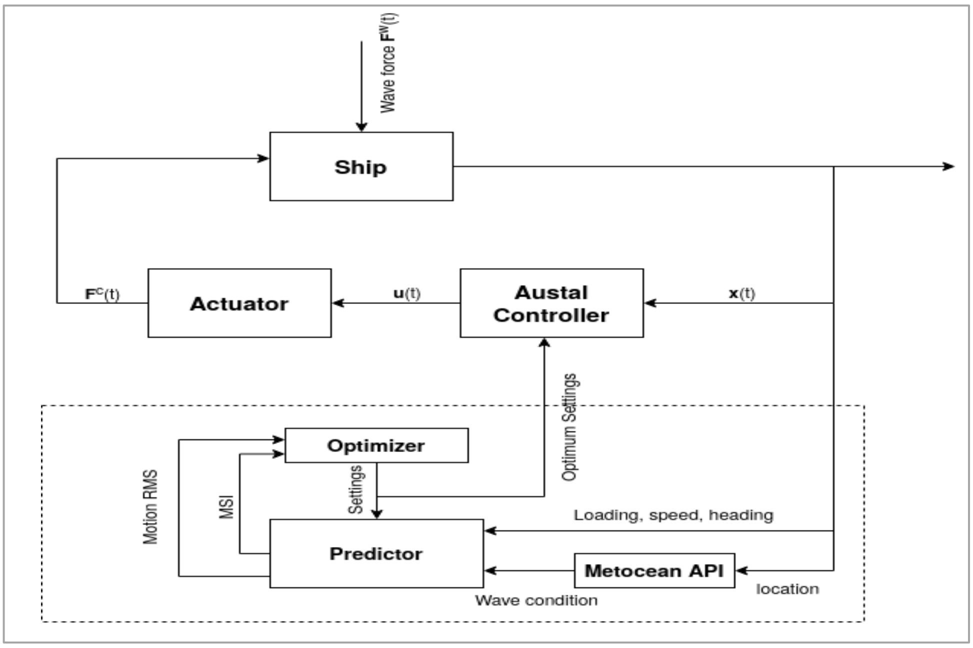
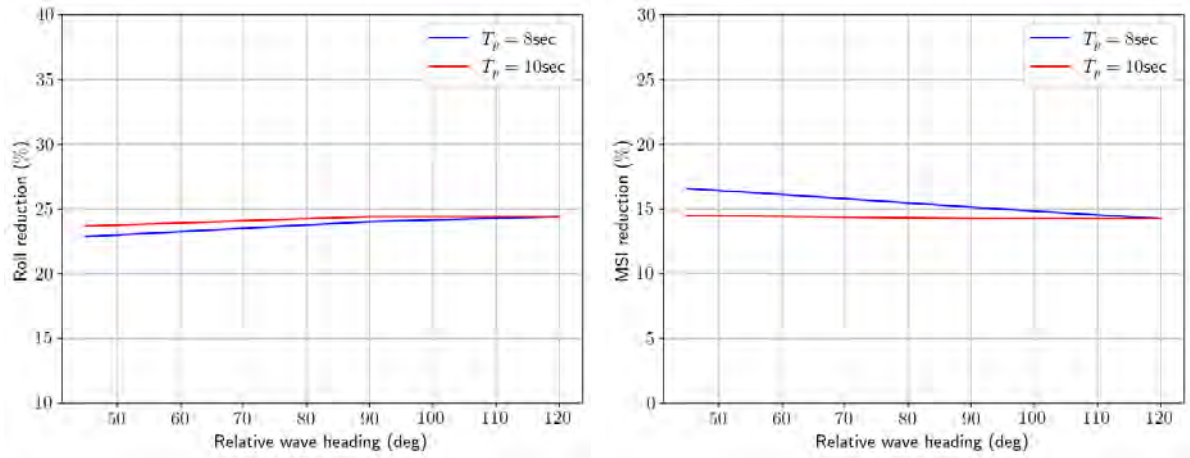


Fig.3: Predictive controller

Fig.4 shows the influence of the advisory system on reducing the roll RMS and MSI (calculated as the average across the passenger deck) of a vessel compared to the fixed settings generally used. It can be observed that the online on-board optimization can reduce the roll RMS and MSI by up to 25% and

15%, respectively. It is worth noting that although the controller does not directly respond to heave acceleration (and consequently MSI) by properly adjusting the coefficients, the MSI can also be reduced as roll and pitch motion have a vertical component.



(a) roll RMS reduction (b) MSI reduction

Fig.4: Influence of on-board advisory system on reducing roll RMS and MSI

The results suggested that by predicting the vessel response to encountering sea-state and performing onboard optimisation of controller settings, it is possible to improve vessel motion and reduce motion sickness. However, it is possible to further improve motion by adjusting the command to control surfaces for any encountering wave. This can be done by using more advanced control strategies such as Model Predictive Control (MPC) or Reinforcement Learning (RL) based control. The capabilities of MPC and RL in reducing undesired vessel motion will be presented in future papers.

4. Conclusions

Here, we presented a predictive control strategy to reduce roll motion RMS and MSI. The presented strategy utilises a predictive model derived from gathered operational data to accurately predict the vessel response to environmental conditions. It then uses an on-board optimisation using Genetic Algorithm to adjust the controller coefficients for given objective functions. The controller efficiency was then analysed at different environmental conditions and showed that such a system can potentially reduce roll RMS by ~25% and MSI by ~15%.

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Creating Method of Standard Specifications for Merchant Ship using Text Mining

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Abstract

This study proposes a novel method to generate standard specifications for merchant ship design from existing specification documents using text mining. It allows shipbuilders a practical way to apply the textual data available in previous specification documents to reduce the workload in the contract design phase. The method was verified through a case study with 98 specification documents of a series of merchant ships. The results show that the selected specification documents are superior to the original standard specification documents used in practice.

1. Introduction

As the world of manufacturing adapts to an eco-friendly environment and embraces the challenges of becoming a digital industry, merchant ship manufacturing companies have begun to devote much attention to improving production efficiency by applying new technologies to the ship design and construction process. Ship design can be broken down into four main phases: concept design, preliminary design, contract design, and detailed design. Among these, contract design, which details the final systems with the shipowner's agreement, needs many person-days to complete because many relevant factors, such as the price, date of delivery and supplier credit should also be taken into account, *Papanikolaou (2014)*. In contract design, the shipbuilder always prepares a standard specification that describes all the required physical and functional characteristics of a ship, service, or construction, for the shipowner based on their essential requirements, *Eyres (2006)*. In practice, shipbuilders always submit a specification of a constructed merchant ship as a standard specification to the shipowner for reference. Due to the shipowner's additional requirements, complex constraints in ship design, and unclear correspondence between contents of specifications, shipbuilders have to spend a long time making the final building specification in negotiation and cooperation with the owners' technical staff. Therefore, to improve product design efficiency, generating specification standards for merchant ship design based on transparent relationships between specifications is necessary for optimizing the merchant ship design process.

Generally, a formal specification document consists of several parts, depending on the functions that can be subdivided into sections and chapters. Moreover, specification documents of a series of merchant ships are written in the same outline with a high similarity of contents and various optional design variables based on shipowners' particular requirements. Influenced by many factors, including shipowners, construction time, rules and regulations, etc., specifications will naturally form several subtypes, in which the complexity between chapters' relations is relatively reduced compared to that of the whole. Therefore, generating a standard specification from each subtype significantly reduces the shipbuilder's workload in contract design. As a method to discover unknown information by automatically extracting information from different written resources, text mining is applicable for generating standard specifications for merchant ship design.

In this paper, we provide new insights into the method of generating standard specifications based on specification document analysis using text mining. By classifying the specification documents and determining the relationships between chapters of specification documents using text mining, we establish a system to find standard specifications that can reduce modifications and rework in the design process, which can improve the efficiency and productivity in merchant ship manufacturing.

2. Generating standard specification using text mining

In this section, we first provide the overview of the standard specification generating system. Then, we explain the details of the two main phases of the system, namely, generating candidates for the standard specifications and evaluating the candidates to determine the standard specifications.

2.1 System overview

Fig.1 shows an overview of the standard specification generating system. The objective of the system is to select standard specifications from the several specification documents of completed orders. Therefore, the system continuously conducts a routine to select the candidates for standard specifications and compares them to generate standard specifications.

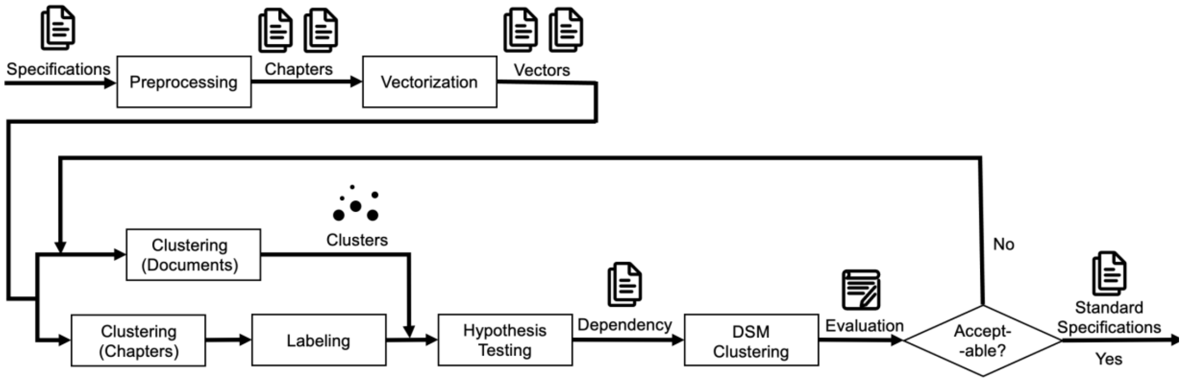


Fig.1: Overview of the Standard Specification Generating System

Initially, the given specifications are preprocessed and separated into chapters for a better analysis. Based on the processed documents, the TF-IDF generates vectors of the specified specification documents. The clustering algorithm can be applied to divide the specified specification documents into clusters, from which the candidate for the standard specifications is selected.

Based on vectorization, chapters can be divided into categories and denoted by nominal variables. The dependency of every two chapters in the same cluster can be obtained using hypothesis testing. After DSM clustering in each cluster, the total complexity in clustering results can be measured, which is used as an indicator to determine the standard specifications.

2.2. Generating candidates of the standard specifications

Here, we propose an approach to cluster specified specification documents and select candidates in each cluster.

2.2.1 Vectorization of specification documents

Text vectorization is a crucial step in text mining that converts text to vectors consisting of continuous quantities readable for machines. Term Frequency-Inverse Document Frequency (TF-IDF) is one of the most common embedding methods in information retrieval and NLP, which assigns weights to words to reflect its importance or amount of information for a document in the collection, *Aizawa (2003)*. Therefore, we propose using the TF-IDF scheme to implement the vectorization of specified specification documents.

After removing commonly used stopwords from the corpus, vocabulary can be built for TF-IDF, and the TF-IDF value of word *i* in document *j* can be calculated as:

$$TF\text{-}IDF_{i,j} = \frac{n_{i,j}}{\sum_k n_{k,j}} * log\frac{|D|}{|j:w_i \in j|} \quad (1)$$

where $n_{i,j}$ denotes the number of words i in document j, $|D|$ denotes the number of documents in the collection, and $|j: t_i \in j|$ denotes the number of documents containing the word i. After calculating all the TF-IDF values of the words in the vocabulary, a given specification can be represented by a vector of continuous quantities.

2.2.2 Clustering of specification documents

From section 1, the problem of generating the standard specifications has been converted to finding the clusters in which the relations of chapters are simple enough for effective contract design. Therefore, the clustering of specification documents is a significant step in this system. In this study, we considered the clustering based on the similarity of document content denoted by the vectors obtained by TF-IDF and based on the likely influential factors chosen from experience.

For clustering based on similarities, two classical clustering algorithms are proposed: agglomerative hierarchical clustering using Ward's criteria, *Ward (1963)*, and the K-means algorithm, *Lloyd (1982)*. In the hierarchical clustering method, the specified specification documents are intended to merge using a bottom-up approach to minimize the error sum of squares (ESS) within all clusters. The K-means method divides the specified specification documents into given K clusters to choose K centroids to minimize the inertia calculated by:

$$\sum_{i=0}^{n} \min_{\mu_j \in C} \left\|x_i - \mu_j\right\|^2 \quad (2)$$

where μ_j is the centroid of cluster j.

Apart from the similarity of contents, other factors that potentially affect the relations between chapters, such as shipowners and construction time, should also be considered to make the clusters.

2.2.3 Selection of standard specification in clusters

To generate candidates of the standard specifications from the obtained clusters mentioned in Section 2.2.2, the specification whose vector is closest to the central vector in its cluster in Euclidean space is selected as the candidate for the standard specification for its cluster. From the case study, it can be proved that this scheme can effectively reduce the workload of modifying in the contract design process.

2.3. Evaluation of the standard specification candidates

With the candidates for the standard specifications generated, as mentioned in Section 2.2, the candidates are evaluated, and the standard specifications that maximize the efficiency in contract design are determined.

2.3.1. Labelling and correlation detection

For efficient contract design, the complexity of the chapters' dependencies in a cluster should be as simple as possible. To detect the correlation between chapters in a cluster, statistical hypothesis testing is proposed to test the dependency between every two chapters in the same cluster. Therefore, hierarchical clustering is conducted in each chapter, and each chapter is labelled based on the similarity of the chapters' contents. Therefore, each given standard specification document can be represented by a series of nominal variables from which the contingency table can be made to conduct dependency testing. Table I presents an example of a contingency table of chapter I and II, where A_i and B_j are labels of chapter I and II, respectively.

Table I: Example of a contingency table of chapter I & II

Chapter I / Chapter II	B_1	B_2	B_3	Row Totals
A_1	k_{11}	k_{12}	k_{13}	R_1
A_2	k_{21}	k_{22}	k_{23}	R_2
A_3	k_{31}	k_{32}	k_{33}	R_3
Column Totals	C_1	C_2	C_3	n

For computational efficiency, the chi-squared test is used in the vast majority of cases. The chi-squared test is a classical test of dependency that checks whether A_i are independent of B_j by calculating the test statistics:

$$d_2 = \sum_{i=1}^{r}\sum_{j=1}^{c}\frac{\left(k_{ij} - n\hat{p}_i\hat{q}_j\right)^2}{n\hat{p}_i\hat{q}_j} \tag{3}$$

where $\hat{p}_i$ and $\hat{q}_j$ are the maximum likelihood estimates of $p_i = P(A_i), q_j = P(B_j)$, respectively, *Hogg et al. (2005)*. However, the chi-squared test is feasible only when $n\hat{p}_i\hat{q}_j \geq 5$ for all i and j, whereas in practice, this inequality does not hold for many cases. Accordingly, Fisher's exact test of the $r \times c$ contingency table is employed for the cases not suitable for the chi-squared test. Fisher's exact test is a test of dependency whose p-value can be calculated precisely by:

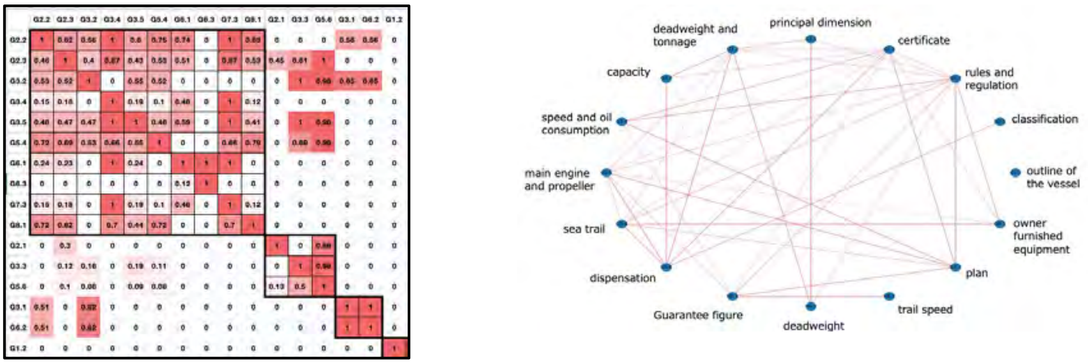
$$\boldsymbol{p} = \sum_{\boldsymbol{Y} \in \varphi} P(\boldsymbol{Y}) \tag{4}$$

where $\varphi = \{\boldsymbol{Y}$: Situations when $P(\boldsymbol{Y}) \leq P(\boldsymbol{X})$ where $\boldsymbol{X}$ is the observed situation in Table I$\}$, rather than relying on an approximation such as the chi-squared test, while its computational efficiency is low, *Mehta and Patel (1983)*. Consequently, all cases of detecting the relations of chapters in a cluster can be managed with a small number of specification documents.

2.3.2. Complexity evaluation based on DSM clustering

The above-obtained relations of chapters in a cluster can be observed in a network diagram, as shown in Fig.2(b). Quantitative measurement of complexity in contract design is required to evaluate the candidates for standard specifications. A complexity metric based on ship types and sizes at the contract design stage was introduced by *Caprace and Rigo (2011)*. However, no complexity metric based on specification documents has been mentioned for contract design. Therefore, the design structure matrix (DSM) is used to measure complexity.

DSM, also known as dependency structure matrix, is a highly flexible network modeling tool representing elements and their interactions within the system to perform analysis and manage complex systems, *Eppinger and Browning (2012)*. To better understand the system architecture that minimizes the complexity and hopefully leads to a quicker and less costly product development cycle, a DSM clustering algorithm has been developed to optimize the subsystem assignment of elements. The entries of the DSM can represent the strength of the interaction, and it has been proven that clustering is significantly improved with the strength of the interaction taken into consideration, *Thebeau (2001)*.



(a) (b)

Fig.2: (a) Clustered DSM and (b) network diagram of 98 specification documents

Therefore, the DSM is constructed based on the adjacency matrix of the network diagram and assigned the strength of the interaction, DSM(i, j), by the influence of chapter i on chapter j, which is defined as the probability that the chapter j should be modified, given that chapter i should be modified. The DSM clustering algorithm is then performed to make the complexity of the chapters' relations in a cluster more intuitive.

2.3.3. Indicators

Based on the abovementioned results, three quantitative indicators are suggested to evaluate the candidates of the standard specifications:

- Dependency complexity: For a group of specification documents whose dependencies between chapters are visualized by a clustered DSM, a modification of the target chapters from the candidate standard specification in this cluster can only consider the chapters in the subsystems containing the target chapters. Therefore, to a certain extent, the workload in this process can be measured by dependency complexity, defined as:

$$\phi = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(ClusterSize_j\right)^2 \tag{5}$$

  where n denotes the number of subsystems in the DSM and m denotes the number of the specification document clusters. In this study, dependency complexity is the primary indicator of candidate evaluation.
- The total number of relations: The workload can also be measured by merely counting the total number of the relations obtained in dependency testing in each specification document cluster.
- Average workload: Supposing all the specification documents in a cluster are derived from the selected standard specification in this cluster, the numbers of chapter changes per document can be seen as a measurement of the workload. Hence, the average workload can be defined as the mean of the chapter changes per document in all clusters of specification documents.

Using the indicators above, the standard specifications that minimize the contract design workload can be determined.

3. The case study

In this section, a case study of generating standard specifications from the 98 specified specification documents of the 63,000 M.T.D/W TYPE BULK CARRIER series of merchant ships using the methods proposed above is demonstrated. The documents consist of four parts: the general part, hull part, machinery part, and electric part. This study only considered the general parts of the 98 documents. After determining the standard specifications for the series of merchant ships, the selected standard specification documents with the three original standard specification documents currently used in the contract design stage are compared.

3.1. Specifications clustering

Table II shows the partial results of the document vectorization using TF-IDF. Weights evaluating the importance were assigned to the words tokenized from the document collection. Therefore, each specification document can be represented by a vector consisting of a series of TF-IDF values.

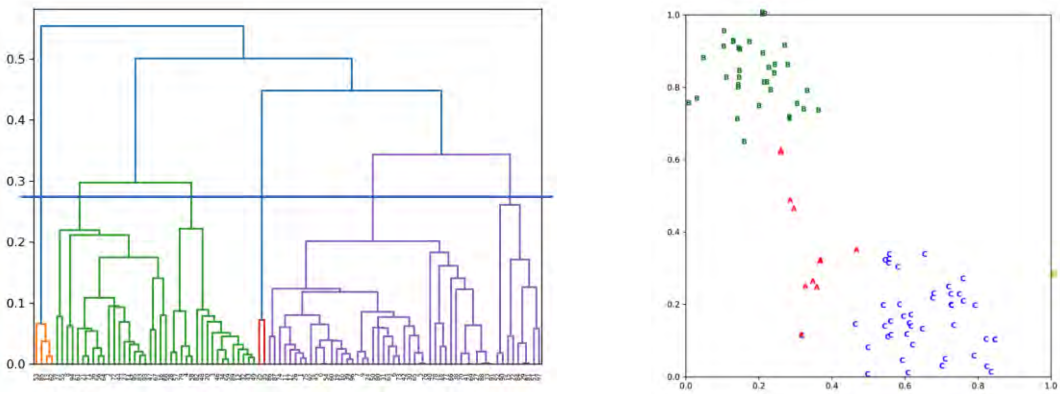
Table II: Partial results of the document vectorization using TF-IDF

ID	lr	abs	korean	kaiji	kyokai
ABC11	0	0	0	0.1163	0.1163
ABC12	0	0	0	0.1146	0.1146
ABC13	0	0	0	0.0873	0.0873
ABC14	0	0.2045	0	0	0
ABC15	0.2110	0	0	0	0

Combined with the design experience and opinions from professional engineers in the shipbuilding industry, four essential influential factors are chosen as the basis of clustering: the content similarity of the general part, the shipowners, similarity of the chapter ‘Rules and Regulations,’ and the construction time.

3.1.1 Clusters based on contents’ similarity of the general part

After calculating the cosine similarities of the specification documents, a dendrogram was used to illustrate the arrangement of the clusters of 98 specification documents. As shown in Fig.3(a), the 98 specification documents can be roughly divided into four clusters of orange, green, red, and purple, in which the orange cluster has four documents, the green cluster has 38 documents, the red cluster has two documents, and the purple cluster has 54 documents. Similarly, the 98 specification documents can be divided into six clusters, as shown by the blue line in Fig.3(a).



(a) Hierarchical clustering (b) K-means clustering visualized by t-SNE

Fig.3 Clusters based on contents’ similarity

Fig.3(b) presents four clusters made by the K-means algorithm and visualized by t-SNE, *Maaten and Hinton (2008)*. A, B, C, and D represent four different clusters: The A cluster has 11 documents, the B cluster has 36 documents, the C cluster has 47 documents, and the D cluster has four documents.

3.1.2 Clusters based on shipowners

According to the information provided by the shipbuilding company, 98 specification documents belong to eight different shipowners from shipowner A to shipowner H. We can obtain eight clusters where each cluster of specification documents has a common shipowner: 15 documents belong to shipowner A, 25 documents belong to shipowner B, eight documents belong to shipowner C, seven documents belong to shipowner D, one document belongs to shipowner E, three documents belong to shipowner F, eight documents belong to shipowner G, and 31 documents belong to shipowner H.

3.1.3 Clusters based on 'Rules and Regulations' chapter's similarity

Based on the information provided by shipbuilding companies, it is learned that different functions of ships might lead to differences in the application of laws and regulations, which can also be used to create clusters of specification documents. Therefore, the similarity of a chapter called 'Rules and Regulations' are used to cluster 98 specification documents, the result of which are presented in Fig. 4. The 98 specification documents can be roughly divided into three clusters of orange, green, and red, in which the orange cluster has four documents, the green cluster has 39 documents, and the red cluster has 55 documents. By analysing the textual contents of this chapter, it is found that the rules and regulations can also be roughly divided into three types, which correspond to the dendrogram results.

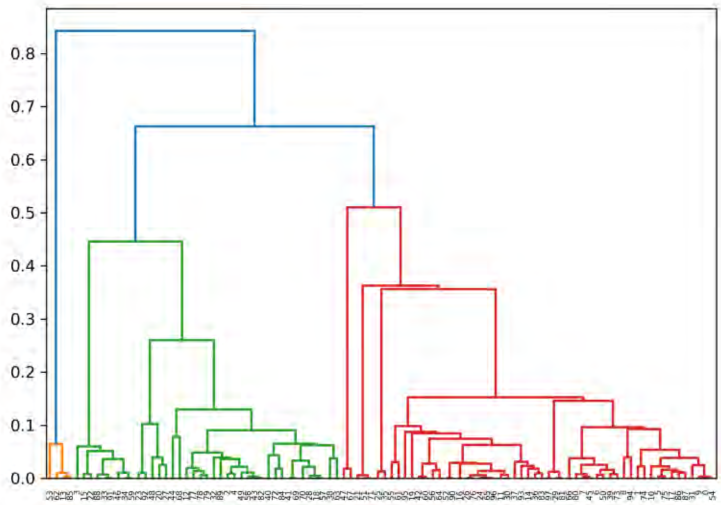


Fig.4: Clusters based on dendrogram of the chapter "Rules and Regulations"

3.1.4 Clusters based on construction time

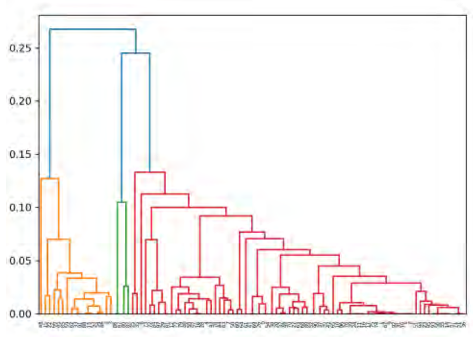
Depending on the time of construction, the design variables of the ship may vary greatly, as the legal provisions and specifications are constantly updated. Therefore, we grouped ships by year and explored the correlation between their internal chapters. The specification documents of the 98 ships were completed between 2013 and 2019: with one in 2013, 13 in 2010, 22 in 2015, 14 in 2016, 21 in 2017, 23 in 2018, and seven in 2019, as shown in Table III. To facilitate the analysis, 2013 and 2014 are arranged in the same group so that there were seven clusters based on construction time.

Table III: The construction time

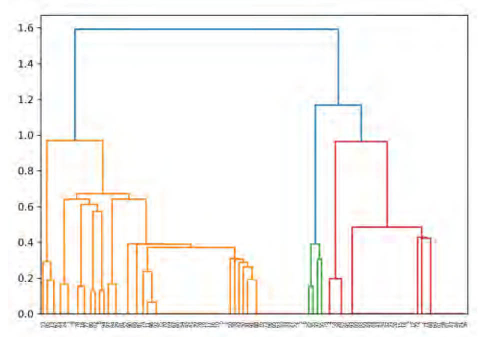
Time	2013	2014	2015	2016	2017	2018	2019
Documents	1	10	22	14	21	23	7

3.2. Evaluation of the standard specifications' candidates

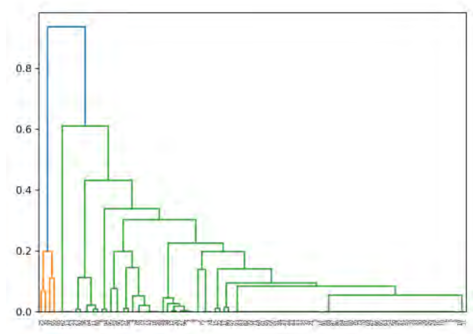
Fig.5 shows the partial results obtained from the hierarchical clustering of each chapter. According to the dendrograms, the clustering results are labeled to distinguish different contents in every chapter, except for several chapters classified by the shipbuilding company as contents with no influence on the contract design.



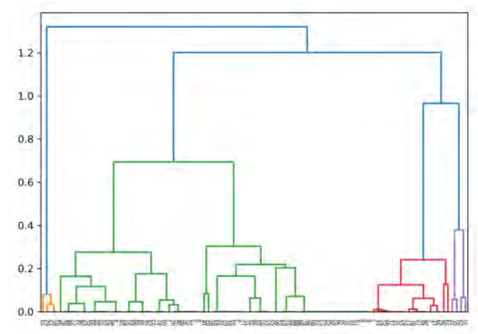
(a) Certificate



(b) Deadweight and Tonnage



(c) Capacity



(d) Main Engine and Propeller

Fig.5: Partial dendrograms of chapters

After labeling, each specification document can be represented by a series of nominal variables, as shown in Table IV. Next, Fisher's exact test and the chi-squared test are used to examine the dependency of chapters of specification documents within one cluster. A DSM clustering algorithm is performed in each cluster to analyze the complexity of the chapters' relations in the cluster.

Table IV: Partial results of labeling based on chapters' content similarity

ID	G1.2	G2.1	G2.2	G2.3	G3.1	G3.2	G3.3
ABC00	B	A	C	E	A	A	B
ABC12	B	A	B	E	B	C	B
ABC13	B	A	A	A	A	A	B

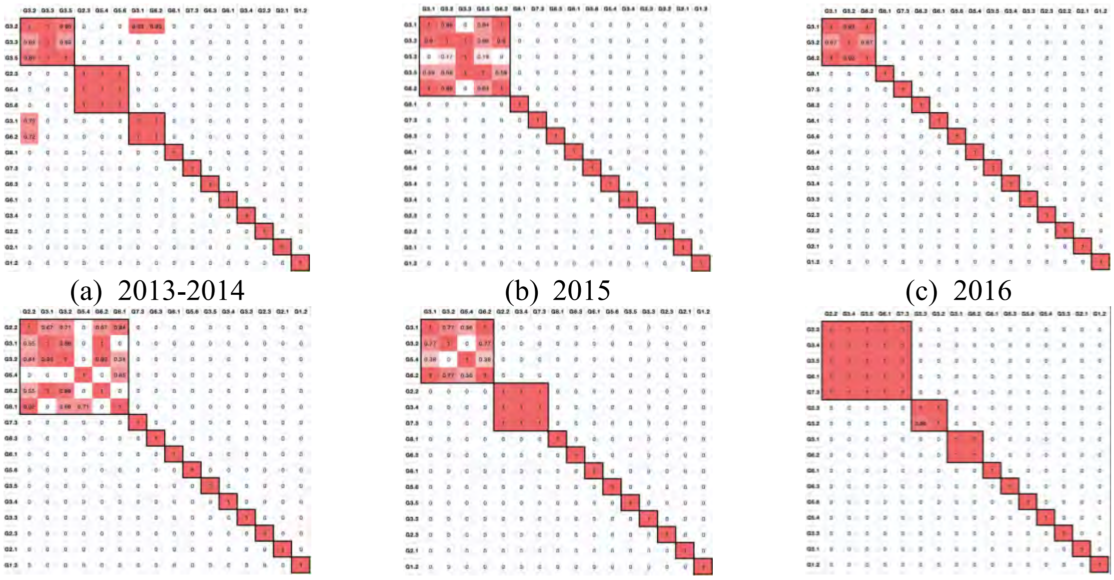
After conducting the routine mentioned above for all the clustering results mentioned in Section 3.1 and evaluating them using the indicators proposed in Section 2.3.3, the evaluation results can be summarized in Table V.

Table V: Evaluation of clusters in chapter 3.1

Clusters		Dependency complexity	Total number of relations	Average workload
Similarity	2 clusters (dendrogram)	8248	5008	11.26
	4 clusters (dendrogram)	4358	940	5.42
	3 clusters (K-means)	13386	41	4,91
Shipowners	8 clusters	5368	1658	4.85
Rules and Regulation	3 clusters	5058	1696	5.93
	4 clusters	4252	937	5.73
Construction time	6 clusters	3320	676	5.42

It is observed that the cluster in which 98 specification documents are divided into six groups according to the construction time is the most reasonable classification method according to the proposed indicators, as shown in Table V.

Fig.6(a) to Fig.6(f) show the DSMs of groups in the time cluster, in which the values represent the degree of influence between chapters. The DSMs of the clusters are more straightforward than those of the 98 documents, which indicates that the relationships between chapters are much simpler than 98 specification documents analyzed as a whole cluster.



(a) 2013-2014 (b) 2015 (c) 2016

(d) 2017 (e) 2018 (f) 2019

Fig.6: The DSMs of clusters based on construction time

In each cluster, the specification document whose vector is the closest to the center vector of the cluster is selected as the candidate for the standard specification for the cluster and compared with the original standard specifications used in the contract design currently by the average workload in the cluster. The results are shown in Table VI, which illustrates that the selected standard specifications have better performance than that of the original standard specifications.

Table VI: Standard specification document comparison

	ID		Average workload in the cluster
Original standard specification documents	Doc1		10.7
	Doc2		11.2
	Doc3		11.8
Selected standard specification documents	2013-2014	ABC65	6.63
	2015	ABC96	4.41
	2016	ABC26	3.36
	2017	ABC06	4.81
	2018	ABC12	7.74
	2019	ABC28	5.14

5. Conclusions

This study introduces the development of a standard specification formulation method for merchant ship design using text mining. A framework and details in each stage of this method were provided, followed by a case study to generate the standard specifications from 98 specified specification documents.

As the case study indicates, text mining makes good use of the text data generated in the previous design process and can effectively vectorize and cluster specification documents. The correlation between texts based on chapters is clarified through the labeling and correlation detection of specification document clustering results, which provide a useful reference for designers in the design process of modifying the standard samples until the requirements are met. By selecting the specification whose vector is closest to the cluster centroid as the standard specification, the contract design's workload can be reduced.

In the future, to generate more applicable standard specifications for merchant ship design, figures in specifications should also be taken into consideration. Further, heuristic methods are to be applied to find the optimal cluster arrangement in future work.

Acknowledgment

We thank Imabari Shipbuilding Co., Ltd. for supporting this work.

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An AI-powered Corrosion Detection Solution for Maritime Inspection Activities

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Abstract

This paper presents an AI-powered corrosion detection solution which facilitates decision support for maritime inspection activities. The solution employs a cascade of deep learning-based image recognition algorithms and a low-cost depth camera to detect corrosion and measure its extent in various scenarios. The developed solution will help surveyors to assess corrosion more confidently and consistently. In combination with remote inspection technologies such as unmanned aerial vehicles ("drones"), our new corrosion detection solution is considered to be a building block for future, more automated, ship inspections.

1. Introduction

Corrosion prevention is expensive due to the harsh marine environment. A recent study estimates that "the total cost of marine and offshore corrosion worldwide is between USD 50-80 billion". Fig.1 shows some commonly found corrosion on vessels. Manufacturers often use high-performance coatings to prevent corrosion, but these will eventually show signs of corrosion. The marine industry therefore complies with IACS Recommendation 87, *IACS (2015)*, which divides the coating condition into three grades: GOOD, FAIR and POOR, to assess the coating condition.

Currently, the coating condition is assessed manually by surveyors – not only DNV's but also those of other classification societies. This raises two types of challenges: i) surveyors have to be physically present onboard to carry out their inspection, which is likely to lead to hazardous situations; ii) the assessment of the coating condition relies highly on the surveyor's expertise and ability, thus involving the innate weakness of the human vision system in unfavorable environments and making the assessment prone to inaccuracy and inconsistency.

Fig.1: Illustration of various types of corrosion. From left to right: general corrosion, pitting corrosion, and bacterial corrosion. The pictures are taken from IACS Recommendation 87.

Classification societies and other marine service providers have long striven to develop (semi-) automated inspection tools to boost efficiency and reduce costs. This work has recently accelerated as part of the ongoing digital transformation. American Bureau of Shipping (ABS) is one of the first to apply artificial intelligence models to detect levels of corrosion and coating breakdown on ships, *ABS (2021)*. By leveraging cloud-based AI tools, their method adopts a deep learning-based corrosion segmentation model to assess the corrosion condition from RGB images. A recently completed EU-funded research project – ROBotics technology for INspection of Ships (ROBINS) (Two classification societies, Registro Italiano Navale (RINA) and Lloyd Register (LR), were involved.) – aimed at filling the technology gaps to achieve autonomous ship inspections, for which automatic corrosion detection is a key component through the synergy of robotics and computer vision.

In the above referenced work, the condition of the coating on metal surfaces is assessed using a RGB camera as a sensor. This method lacks effectiveness because the size of a detected corrosion area solely depends on the number of corresponding pixels, without considering the object distance and orientation. To build a coating condition assessment tool that is robust against changes in appearance, a promising solution is to involve 3D information combined with RGB images. The ability to capture 3D information is currently provided by a so-called depth sensor.

Fig.1: Intel RealSense D435i camera for stereo depth solution, https://simplecore.intel.com

In its current prototype stage, our proposed corrosion detection solution uses an Intel RealSense D435i camera, Fig.2. This RealSense device provides hardware-level synchronized RGB and depth images. The next wave of innovation will bring depth sensors as standard to mobile handsets as well as drones. With this technology, our two-tiered corrosion condition assessment method works as follows: firstly, a deep learning-based image segmentation model identifies areas of corrosion (as well as coating breakdown); secondly, the detected corrosion area can be re-projected to 3D world coordinates to determine its physical size. This ability enables a more reliable assessment of the corrosion condition and improves the state of the art. Fig.3 introduces the framework for our methods.

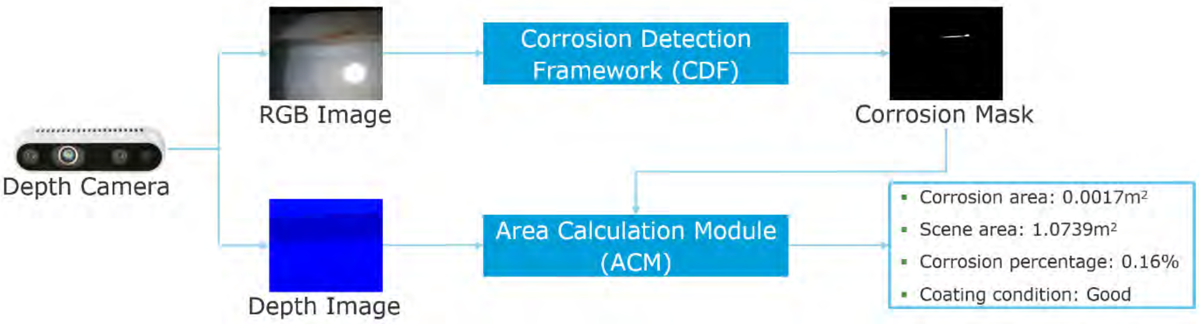

Fig.3: Framework for our method, which consists of two independent modules: a deep learning-based image segmentation module, and an area calculation module.

The method proposed in this paper lends efficient and effective coating condition assessment support to surveyors, shipyards, and other maritime stakeholders. The output of our method is the ratio of the corroded area(s) to the whole tank surface, which helps surveyors make rapid decisions. Once fully implemented and coupled with an inspection drone, this novel approach helps to reduce the efforts required and can make inspection operations safer.

The rest of the paper is organized as follows: Section 2 describes the motivation to develop an automatic inspection process; Section 3 introduces details of methods to detect corrosion areas and then to estimate its physical size using a depth camera; Section 4 reports experimental setups and analyses results; and Section 5 discusses the applications of the automatic inspection process.

2. State of the art

2.1. Coating condition assessment criteria

IACS Recommendation 87 grades the coating condition into three levels: GOOD, FAIR and POOR. Details of each level are listed in Table I. According to IACS, the traditional coating inspection process relies on an inspector to estimate the percentage of the "area under consideration" that has corrosion and coating failures. The grade – provided by the inspector – should be the result of a comparison between the visual inspection and sample diagrams illustrated in Fig.4.

Table I: The coating condition is graded based on the estimated percentage of areas with coating failures and rust surfaces according to IACS Recommendation 87

	GOOD (3)	FAIR	POOR
Breakdown of coating or area rusted (1)	< 3%	3 – 20%	> 20%
Area of hard rust scale (1)	-	< 10%	≥ 10%
Local breakdown of coating or rust on edges or weld lines (2)	< 20%	20 – 50%	> 50%

Notes:
1 % is the percentage calculated on basis of the area under consideration or of the "critical structural area"
2 % is the percentage calculated on basis of edges or weld lines in the area under consideration or of the "critical structural area"
3 spot rusting, i.e. rusting in spot without visible failure of coating

The process lacks efficiency and effectiveness because: i) the inspection activity is done manually; ii) the result of the comparison is subjective. This paper aims to overcome these disadvantages using advanced artificial intelligence algorithms and novel sensor technologies. Please note that this paper focuses on the automatic inspection of the "area rusted" as described in Table I, while inspections of edge corrosion will be our future work.

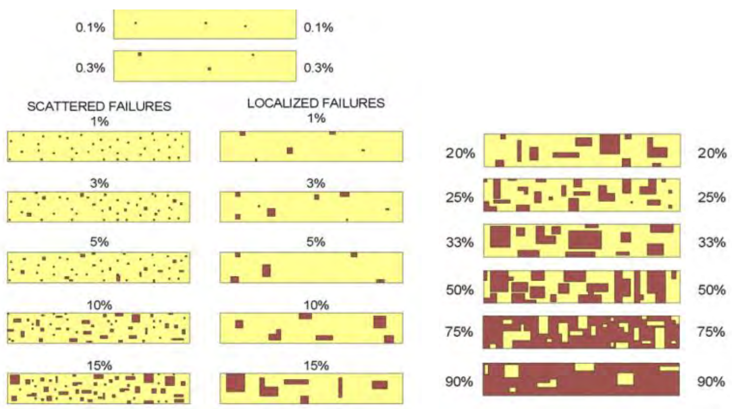

Fig.4: Assessment scale for coating breakdown of IACS Recommendation 87

2.2. Improving corrosion condition assessment using computer vision and depth sensing

The limitations of corrosion condition assessment conducted by human surveyors can be largely alleviated by fusing advanced computer vision together with cutting-edge depth sensing technologies. Computer vision makes corrosion detection more efficient. More importantly, depth information enables the physical sizes of objects to be measured and thus fulfils the prerequisite of an effective condition assessment based on area sizes.

Efficiency: Compared to human vision, which is good at the qualitative interpretation of an unstructured scene, computer vision cuts out repetitive tasks demanding higher accuracy and unbiased results. The recent success of deep learning methods has led to their dominance in nearly all areas of computer vision: image classification, object detection, and semantic segmentation, to name but a few. Therefore, Corrosion.ai adopts deep learning methods in its software component Corrosion Detection Framework (CDF), which uses computer vision algorithms to automatically identify corrosion based on images or videos. Here, we formulate corrosion detection as a semantic segmentation problem. As illustrated in Fig.5, semantic segmentation is a computer vision task that aims to assign a class label to each pixel in an input image. Due to the amorphous nature of corrosion, semantic segmentation is suitable for corrosion detection.

Fig.5: An example of semantic segmentation, *Chen et al. (2017)*

However, the wide range of diverse maritime scenes, Fig.6 - where corrosion can occur - is not easily covered by a single deep neural network. To tackle this, the CDF leverages a cascade of deep learning models, each of which serves an independent purpose, and works as follows: i) a scene classification model is first applied to an input image categorizing the depicted scene; ii) if the image is considered to be taken outside of a ship tank, a non-region-of-interest (non-RoI) removal model will be run; iii) depending on the predicted scene, a corresponding corrosion segmentation model finally segments the corrosion regions in the image. The details of each step will be explained in Section 3.

Effectiveness: Most computer vision applications employ a single RGB camera to capture information. In this process, the real 3D world is projected onto a 2D image and information on the third dimension is lost. While being sufficient for many tasks, the loss of depth information can introduce difficulties to problems where objects' physical dimensions matter, Fig.7. This applies exactly to the case of corrosion condition assessment, where the ratio of two surface areas is of interest and fundamental to the assessment. To address this issue, the proposed solution not only adopts a depth camera as a data acquisition device (sample input is shown in Fig.8), but also introduces a second software module called the Area Calculation Module (ACM). The ACM uses the depth image and coordinates of pixels representing corrosion as input and calculates the area of corrosion, the entire visible area depicted by the image as well as the ratio of both. It can also be configured to output rating grade based on selected rules and regulations, e.g., "GOOD", "FAIR" and "POOR" in IACS Recommendation 87.

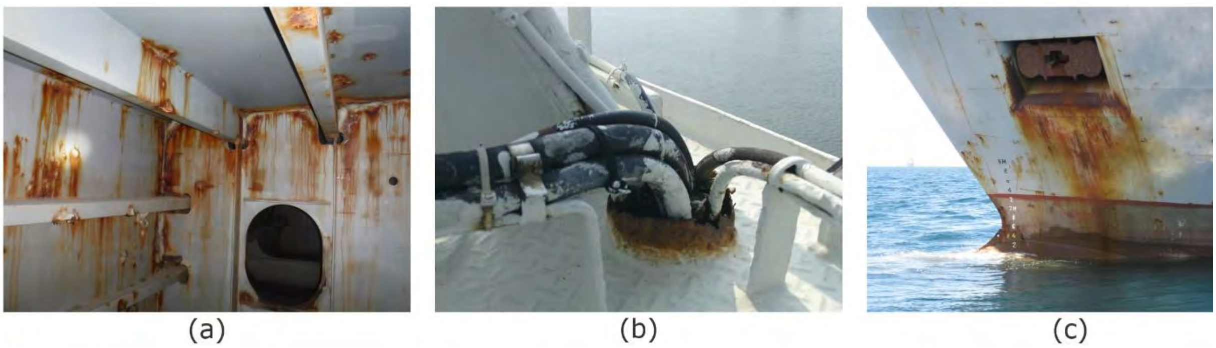

Fig.6: Examples of defined use scenarios: (a) Ballast tank, (b) Deck, (c) Side shell

Fig.7: Computer vision algorithms have difficulty answering the two questions in the image due to the lack of depth information, *Moore (2016)*

Fig.8: Example of pairwise RGB image (left) and depth image (right), where various depth values are represented in different colours. While not visible in the RGB image, the second more distant manhole can still be observed in the depth image.

3. Methods

The proposed automatic corrosion condition assessment solution consists of two independent software components. The first component is the Corrosion Detection Framework (CDF), which identifies pixels representing corrosion from an image. After this processing, each pixel will be classified as either “corrosion” or “non-corrosion” (in the case of an external structure, pixels can be additionally classified as “non-region-of-interest” due to the effect of Non-RoI removal). Then the second component, the Area Calculation Module (ACM) uses the identified set of pixels as input to calculate the area. The two modules will be explained in further detail in the following sections.

3.1. State-of-the-art semantic segmentation

Over the past few years, a multitude of CNN-based semantic segmentation methods have been proposed by the computer vision community. Although these methods employ different techniques and innovations, many of them share an essentially similar structural design which can be decomposed to an encoder module and a decoder module.

The encoder module is usually a modified version of deep Convolutional Neural Networks (CNNs) for image classification (e.g., ResNet-50, *HE et al. (2016)*) where the first layers learn low-level visual concepts while producing high-resolution feature maps. As the network goes deeper, to prevent being computationally infeasible, the feature maps produced by deeper layers will be down-sampled while possessing specialized semantic information. The specialized semantic information has high discriminative power and can be exploited to distinguish between object classes. However, unlike the image classification task, where the only thing that matters is “what” presents the image, the goal of semantic segmentation is to output a full-resolution segmentation mask containing not only class label(s) but also fine spatial information (“where”). Therefore, the feature maps extracted by the encoder module need to be properly leveraged to enable pixel-wise dense prediction and the size of the final output must be identical to that of the input image. This will be achieved by the decoder module and the concrete strategy differs from approach to approach.

3.2. Corrosion Detection Framework

The CDF is composed of three steps and the workflow is illustrated in Fig.9.

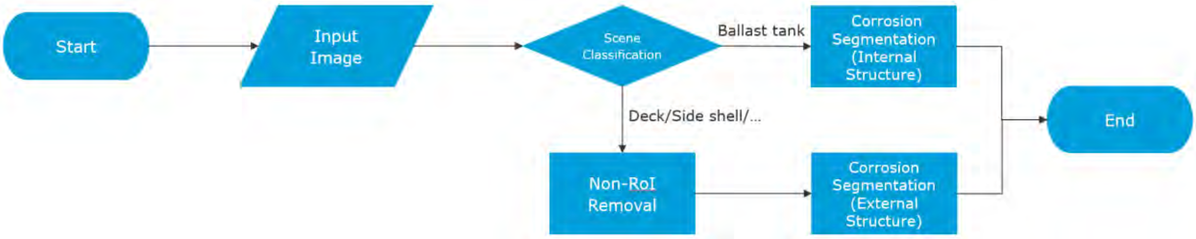

Fig.9: Workflow of the corrosion detection process implemented in CDF

Scene classification step. Given an input image, a fine-tuned classification network with MobileNetV2, *Sandler et al. (2018),* architecture will first categorize it as one of the two defined scenarios: i) internal structure (especially ballast water tanks); ii) external structure (including decks and side shells). As shown in Fig.6, images might be taken from various locations, but most of them belong to either an external or internal structure.

Non-RoI Removal step. In the case of an external structure, an additional step named Non-RoI Removal is conducted to remove irrelevant image regions. The background will be removed by DeepLab v2, *Chen et al. (2017)*, which has been pretrained on COCO-Stuff, *Caesar et al. (2018)*. Corresponding to the specified scenario, pixels belonging to the classes sky, cloud and sea/river/water are regarded as Non-RoI and will not be considered in the further processing. An example demonstrating the function can be found in Fig.10.

Fig.10: Example of the implemented Non-RoI Removal function

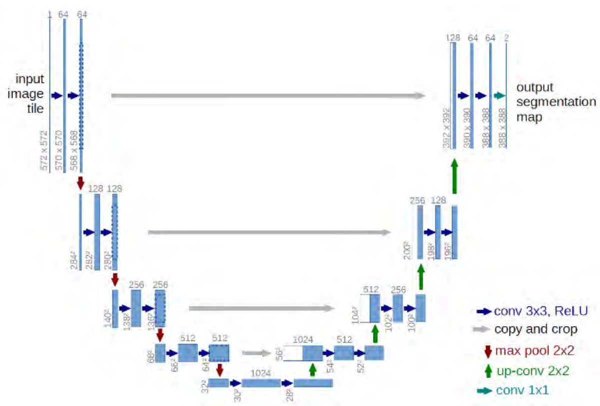

Fig.11: U-Net architecture, *Ronneberger et al. (2015)*

Corrosion segmentation step. The CDF uses U-Net, *Ronneberger et al. (2015),* to segment corrosion in the input image. The elaborate architecture of U-Net, Fig.11, makes it a tool that is well suited not only for biomedical image segmentation but also for corrosion segmentation: i) a concatenation of feature maps from the contracting path (the left half of the "U") provides detailed localization information which enables the precise segmentation in boundary regions; ii) the number of convolutional kernels is halved at each step in the expansion path (the right half of the "U") and at the end this corresponds to the relatively small number of high-level visual concepts appearing in ship coating images. More specifically, two independently trained U-Net models are provided to deal with images of ship internal and external structures respectively.

3.3. Area Calculation Module

According to IACS Recommendation 87, as discussed in Section 2.1, the coating condition is assessed based upon the estimated percentage of areas with coating failure and rusted surfaces. To formulate this formally in our setting : assume set $X \coloneqq \{x_1, x_2, \dots, x_M\}$ contains image pixels representing coating failures and rusted surfaces, while set $Y \coloneqq \{y_1, y_2, \dots, y_N\}$ contains those depicting areas under consideration and $X \subseteq Y$. The percentage can then be defined as a function of X and Y:

$$\Omega(X, Y) = \frac{F(X)}{F(Y)} \tag{1}$$

where F(·) should map pixels back to the physical area according to the rule. A straightforward way to constitute F(·) is to count the number of pixels. In this case, for a set P containing p pixels:

$$F^*(P) = |P| = p \tag{2}$$

However, this only gives an approximate solution and is unreliable and error-prone due to perspective effect and viewpoint variation. To better solve the problem, we propose a software component called the Area Calculation Module (ACM) which directly calculates the physical sizes represented by X and Y with the help of depth information. To be more specific, for a set of pixels Q:

$$F(Q) = F^{\sim}(\varphi(Q)) \tag{3}$$

Where $\varphi(\cdot)$ converts 2D pixels to 3D points, and $F^{\sim}(\cdot)$ measures the area stretched by those points in the 3D space.

The detailed calculation pipeline applied in the ACM is described as follows and illustrated as diagram in Fig.12:

- Pixels in an RGB image representing an area of interest will be converted into 3D points with the help of a depth image.
- Post-processing techniques (e.g., statistical outlier removal) will be performed on the resulting point cloud with the aim of improving data quality and reducing the computational complexity.
- A mesh (triangulated surface) will be generated from the post-processed point cloud using Delaunay triangulation, *Delaunay (1934)*.

Normally, the above-described pipeline will be executed twice - for an area with corrosion and area under consideration respectively. The two results will then serve the purpose of the percentage estimation as dictated by IACS Recommendation 87.

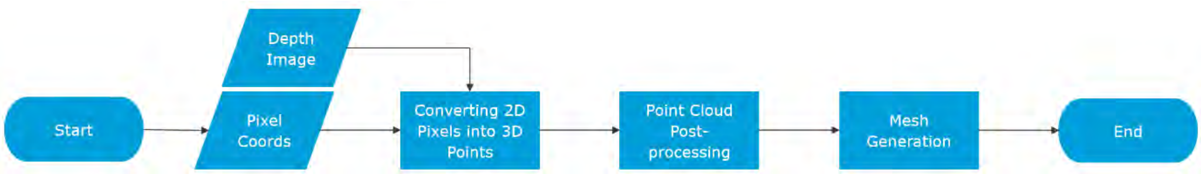

Fig.12: Area calculation pipeline used in the ACM

4. Experiments

This section describes details about the implementation and evaluation of the proposed corrosion detection solution.

4.1. Datasets, evaluation, and implementation of deep learning models

Datasets. In total, four image datasets (details described in Table II) have been constructed to carry out different tasks. The Scene Classification Dataset is image-level annotated and was used for training the scene classification network. The other three are pixel-wise densely annotated. As mentioned in Section 3.2, for performance in both defined usage scenarios (ballast tank vs. deck/side shell), two corrosion segmentation models were developed using the Ballast Tank Dataset and the Deck/Shell Dataset respectively. The Proof of Concept (PoC) Dataset was built for the feasibility study and the selection of model architecture in the early stage of implementation. Since photos taken from different sections of the hull of the same vessel usually share many similar properties (e.g., the lighting condition and coating colour), to guarantee a fair evaluation, the subset split of the Ballast Tank Dataset is such that all images of a certain vessel can only be present in the same subset.

Table II: Overview of curated corrosion datasets

Dataset	Type of annotation	Subset	Number of images	Number of vessels
Ballast Tank Dataset	Pixel-wise	Train	605	10
		Validation	89	1
		Test	226	2
Deck/Shell Dataset	Pixel-wise	Training	163	-
		Test	26	-
Scene Classification Dataset	Image-level	Train	979	-
		Test	268	-
PoC Dataset	Pixel-wise	Train	78	-
		Validation	43	-
		Test	25	-

Pixel-wise annotation. Except for the Scene Classification Dataset, the other three datasets were pixel-wise annotated ("labelled") using the open source image manipulation tool GIMP. The annotation was conducted by students trained by expert surveyors, under the supervision of AI experts. Special attention was paid to several things during the annotation process, Fig.8:

- Rust drips: due to the high humidity and frequent presence of liquid in ship hulls, rust drips can often form. However, they are not corrosion and normally constitute no threat to the asset integrity. By observing the difference in texture, human annotators can distinguish them from corrosion in most cases.
- Items not belonging to the hull structure: any miscellaneous item (e.g., the ladder in Fig.13) which does not belong to the hull structure will be neglected during annotation since corrosion on it will not pose any risk to the hull structure.
- Through-hole area: any corrosion located on the surface which can only be seen through a hole will not be annotated as it may introduce error into the corrosion percentage calculation.

Evaluation. For all developed semantic segmentation models, the Intersection over Union (IoU) metric (also referred to as the Jaccard index) was used for reporting model performance. The IoU measures the percentage of overlapped mask pixels in the total number of pixels across both predicted and ground truth (target) masks:

$$IoU = \frac{target \cap prediction}{target \cup prediction}$$

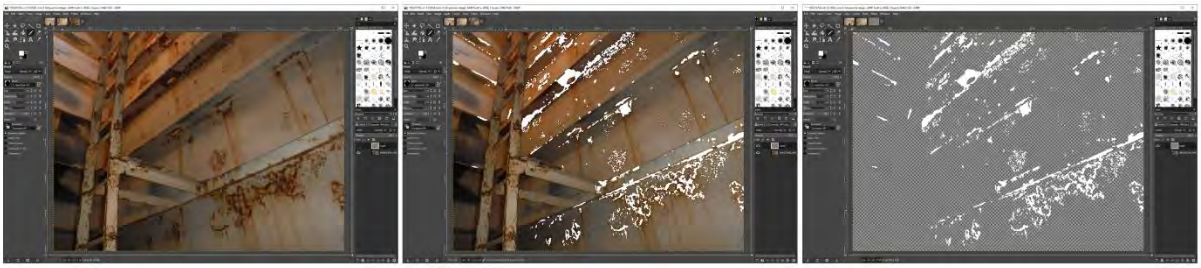

Fig.13: Using GIMP to generate a pixel-level corrosion annotation (left: GIMP user interface with original image; middle: annotation result with original image displayed underneath; right: annotation result with transparent background)

For image classification models, accuracy was used for model evaluation. This is the fraction of model predictions that turn out to be correct and has the following definition:

$$Accuracy = \frac{Number\ of\ correct\ predictions}{Total\ number\ of\ predictions}$$

Deep learning models. All deep learning-based models in this work were implemented using the open source machine learning framework PyTorch, *Paszke et al. (2019)*. Table III gives an overview of these models and the associated datasets on which their development was based.

Table III: Overview of all deep learning models deployed in CDF

Model	Type	Dataset
Scene Classification Model	Image classification	Scene Classification Dataset
Non-RoI Removal Model	Semantic segmentation	COCO-Stuff
Corrosion Segmentation Model – Internal Structure	Semantic segmentation	Ballast Tank Dataset
Corrosion Segmentation Model – External Structure	Semantic segmentation	Deck/Shell Dataset

The Scene Classification Model was implemented by fine-tuning the PyTorch's official Mobile-NetV2, *Sandler et al. (2018),* implementation in the torchvision package. The network's original weights were obtained via pre-training on the ImageNet dataset, *Russakovsky et al. (2015)*. During the fine-turning of the model (or the so-called transfer learning), the Scene Classification Dataset – Train, containing 979 images of both internal and external structures, was utilized as training data. Details of the training hyperparameters used can be found in Table IV. The deployed model utilizes the weights that achieved the highest accuracy in the Scene Classification Dataset - Validation.

Table IV: Hyperparameters used while training the Scene Classification Model

Hyperparameter	Value
Input size	320 × 320
Optimizer	Adam, *Kingma et al. (2014)*
Learning rate	10^{-3} (10^{-5} from the 61st epoch)
Weight decay	$5*10^{-5}$
Number of epochs	100
Batch size	32

The Non-RoI Removal Model was implemented using the DeepLab v2 semantic segmentation model pretrained on the COCO-Stuff dataset (code and model weights are from *Nakashima et al. (2020)*).

Despite being constituted as a semantic segmentation setting as well, the task to be solved here has a different emphasis. While the appearance of corrosion on a vessel is unique and relatively uniform, that of sea, sky, and other stuff defined as Non-RoI can vary widely. The focus of this task should be on the model's generalization capability, i.e., how well can the model react to unseen data. Based upon that, instead of collecting own data and training a customized model, it was decided to employ a model which had been pre-trained on a large-scale dataset containing all defined Non-RoI classes. Of the public datasets with pixel-level annotation, COCO-Stuff has the largest number of images and covers the most "stuff" classes, Fig.14. According to the authors of COCO-Stuff, compared to thing classes, stuff classes are object classes which do not have characteristic shapes or identifiable parts while being highly variable in size and uncountable. Classes which were identified to be Non-RoI can all be found in the stuff classes of COCO-Stuff. To be specific, they are "clouds", "river", "sea", "sky", and "water-other". To improve the inference speed, DeepLab's fully connected Conditional Random Field (CRF) module, which was originally used to improve localization performance is not activated in the CDF.

Dataset	Images	Classes	Stuff classes	Thing classes	Year
MSRC 21 [46]	591	21	6	15	2006
KITTI [23]	203	14	9	4	2012
CamVid [7]	700	32	13	15	2008
Cityscapes [13]	25,000	30	13	14	2016
SIFT Flow [36]	2,688	33	15	18	2009
Barcelona [50]	15,150	170	31	139	2010
LM+SUN [52]	45,676	232	52	180	2010
PASCAL Context [38]	10,103	540	152	388	2014
NYUD [47]	1,449	894	190	695	2012
ADE20K [63]	25,210	2,693	1,242	1,451	2017
COCO-Stuff	163,957	172	91	80	2018

Fig.14: Overview of pixel-level annotated datasets, *Caesar et al. (2018)*

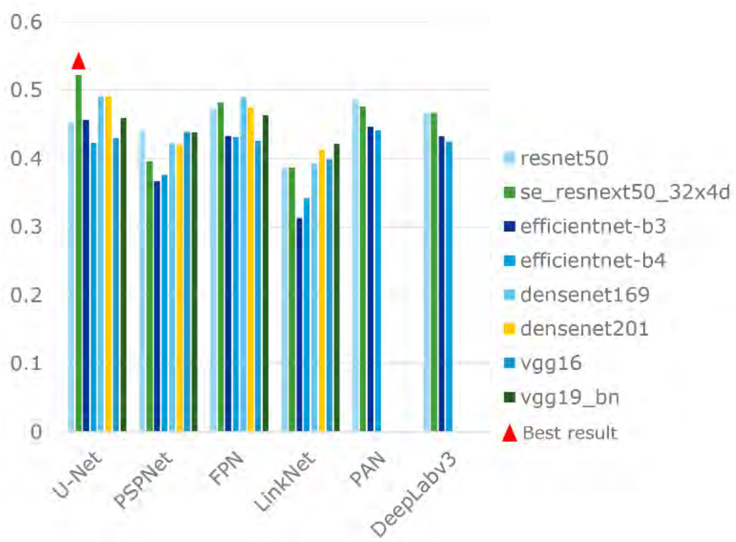

Fig.15: Intersection-Over-Union (IoU) scores achieved on the PoC Dataset - Validation using different encoder network and semantic segmentation approach combinations

As mentioned previously, most of the modern semantic segmentation approaches can be matched with a good choice of encoder networks. Among the 40 combinations of state-of-the-art semantic segmentation approaches and encoder networks (code and pre-trained weights borrowed from the Segmentation Models library, *Yakubovskiy (2020)*), the U-Net, *Ronneberger et al. (2015),* with SE-ResNeXt-50, *Hu et al. (2018),* as an encoder proved to be the most effective in dealing with the corrosion segmentation problem. This combination vastly outperformed the others with an IoU score above 0.5, Fig.15. The selection was conducted by training and evaluating all possible combinations on the dedicated Proof of Concept (PoC) Dataset. This process is comparable to the grid search method in machine learning which is used to optimize the hyperparameters of a learning model.

In machine learning, there is a set of parameters that cannot be learned during model training. Instead, these so-called “hyperparameters” serve to control the learning process. After selecting the architecture for corrosion segmentation models, hyperparameter tuning has been conducted on the validation set of the Ballast Tank Dataset. The resulting settings are listed in Table V and have been applied to the training of the external structure model on the Deck/Shell Dataset as well.

Table V: Hyperparameters used during the training of Corrosion Segmentation Models

Hyperparameter	Value
Input size	800 × 800
Optimizer	Adam
Learning rate	10^{-4} (10^{-5} from the 61st epoch)
Weight decay	$1.5*10^{-5}$
Number of epochs	100
Batch size	8

4.2. Hardware setup and ACM implementation

Hardware setup. To enable the testing of the implemented software solution live in the field, portable test equipment, Fig.16, was built with Microsoft Surface Go 2 as its core. Two Intel Real-Sense sensors, a D435i depth camera and T265 tracking camera are mounted on the back of the tablet PC via a 3D printed mounting part. In total, the implemented kit weighs less than 2 kg, making it a well-suited mobile computing and data acquisition platform for the confined ship hull environment. With the help of the T265 tracking camera, in-door localization can also run on the device while it is capturing RGB-D data. However, this is outside the scope of this paper and will not be discussed any further here.

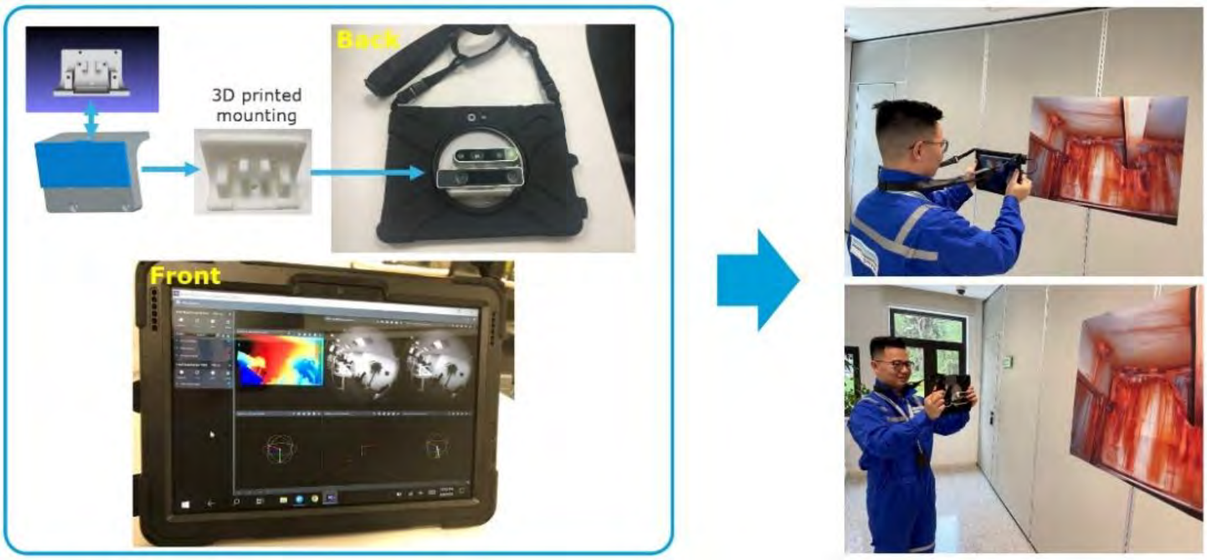

Fig.16: The implemented test equipment and its usage demo

ACM implementation. With a selected set of RGB pixels of interest and the corresponding depth image captured by the RealSense D435i, 3D points making up the 3D surface(s) can be retrieved with the help of a built-in function implemented in the RealSense SDK. Pre-processing techniques for point clouds, i.e., voxel downsampling and statistical outlier removal, were implemented using the open source 3D data processing library Open3D, *Zhou et al. (2018)*, developed by Intel. For mesh generation, Delaunay triangulation implementation using the mesh analysis tool PyVista was utilized, *Sullivan et al. (2019)*.

4.3. Results

CDF. The results of evaluating individual CDF modules are summarized in Table VI. All metrics are reported on the test set of each task's corresponding dataset. Examples of both corrosion segmentation models' outputs can be seen in Fig.17.

Table VI: Evaluation results of the corrosion segmentation models

Model	Type	Dataset	Number of images	Result
Corrosion Segmentation Model – Internal Structure	Image segmentation	Ballast Tank Dataset - Test	226	0.4011 (IoU)
Corrosion Segmentation Model – External Structure	Image segmentation	Deck/Shell Dataset - Test	26	0.4652 (IoU)
Scene Classification Model	Image classification	Scene Classification Dataset – Test	268	0.9851 (Accuracy)

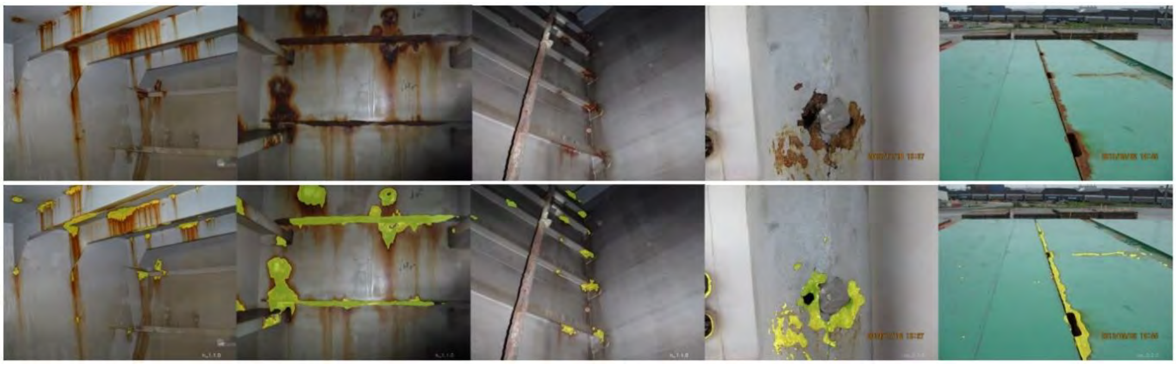

Fig.17: Results of the developed corrosion segmentation models. The left three images are from Ballast Tank Dataset – Test and processed by the in-hull corrosion segmentation model. The right two images are from the Deck/Shell Dataset – Test and processed by the external structure corrosion segmentation model. Predicted corrosion areas are highlighted in light green.

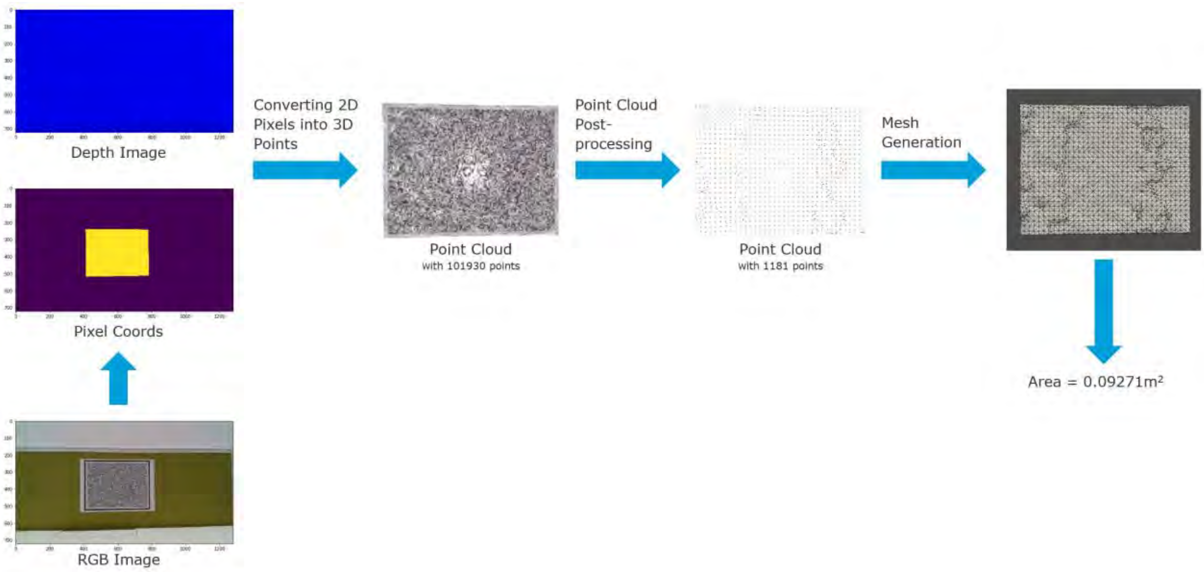

Fig.18: A concrete example of the area estimation process with visualized input/output at each step

ACM. Since no large-scale dataset has been created for evaluating the implemented ACM, its performance is demonstrated through an application case illustrated in Fig.18. The texture pattern printed on A4 paper is used as the region of interest in the example and its extent needs to be estimated using the proposed approach. Pixels of the pattern are segmented manually using GIMP which imitates the automatic corrosion segmentation process performed by the CDF. The ground truth, result and deviation are given in the form of numerical values in Table VII.

Table VII: Relevant data of a real area estimation example

Ground truth			Result	Deviation	
Height (m)	Width (m)	Area (m^2)	Area (m^2)	Absolute (m^2)	Relative (%)
0.268	0.357	9.568×10^{-2}	9.271×10^{-2}	0.297×10^{-2}	3.105

4.4. Computational cost

To measure the computational cost of our solution, the run of each processing step has been gauged on our workstation. The workstation has an Intel Xeon Gold 6242 CPU @ 2.80GHz and three NVIDIA Quadro RTX 6000 GPUs. The detailed running time is reported in Table VIII. In the current implementation, it is the single-threaded pixel-to-point conversion that takes most of the time and has great potential for improvement. Moreover, the processing time for the point cloud is strongly dependent upon the number of points in a point cloud. Therefore, the CPU seconds for the ACM listed in the table is for reference purposes only.

Table VIII: CPU seconds for each processing step and the entire pipeline

CDF			ACM		
Scene classification step	Non-ROI removal step	Corrosion segmentation step	Pixel-to-point conversion	Delaunay triangularization	Total
0.03 s	0.52 s	0.16 s	3.75 s	0.72 s	5.18 s

5. Applications

At present, coating condition monitoring is mostly based on close-up visual examinations. To facilitate safer, more cost-optimized inspections, maritime industry players are developing remote inspection applications, following similar experience in domains such as the energy and aerospace industries. In this section, we shed light on automatic inspection of the coating condition with the support of mobile devices and unmanned aerial vehicles (UAVs).

Mobility is one of the crucial factors for conducting automatic inspection activities. A simple yet effective solution is to run corrosion detection on mobile phones. However, this solution still requires surveyors to enter a ship tank. Instead of human beings, specifically designed UAVs which have emerged on the market recently could be sent to hazardous places and dangerous situations. Among various types of UAVs, drones enable the on-edge operation of computer vision algorithms while being controlled remotely or flying autonomously. Fig.19 shows a set of video frames captured by a flying drone, where corroded areas (detected by our method) are highlighted. The video was taken inside a ship tank during DNV's research project ADRASSO, *Stensrud et al. (2020)*. As seen from these results, our method – when combined with a drone – provides quick decision support while reducing risks to surveyors.

Instead of UAVs, an alternative way to conduct a remote corrosion inspection is to use Augmented Reality (AR) technologies. AR reduces physical movement and provides context-sensitive support and real-time traceability. Nowadays, many AR devices (e.g., smart glass and smart helmets) have become cheaper and lighter. Junior surveyors and/or ship crews could carry AR devices on board while expert surveyors could conduct verifications and make decisions remotely. In such a case, the solution proposed in this paper could run remotely while its results could enhance the real-time onboard video stream via a high-speed 5G network.

Fig.19: Top: video frames taken by a flying drone inside a water ballast tank. Bottom: corrosion area (highlighted) detected on each video frame.

6. Summary and future work

In summary, this paper has proposed an AI-powered corrosion detection solution and has demonstrated its feasibility for coating condition assessment and outlined its ability to take part in remote inspections. Our solution is composed of two modules: a corrosion detection framework (CDF) module to accurately segment the corroded area regardless of image types; and an area calculation module (ACM) – when combined with a depth senor – to enable physical measurement of the corrosion area. Experiments on various corrosion detection tasks show that the proposed method performs well in terms of accuracy and computational efficiency.

According to IACS Recommendation 87, edge corrosion (local breakdown of coating or rust on edges and weld lines) needs to be assessed separately. We therefore plan to implement edge corrosion detection with the help of a 3D reconstruction technique which provides rich information about structural components.

Finally, a User-Interface (UI) tool is needed with which surveyors are able to interactively select the area under consideration as dictated by IACS Recommendation 87. Currently, our solution treats the entire input image as the area under consideration. In practice, surveyors need to use their experience to adjust the targeted hull area. The ultimate aim would be to create situational awareness for a remote surveyor, so as to enable decision making based on remotely collected data and automated image analysis.

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Secure, Trustworthy and Efficient Information Exchange – Enabling Added Value through the Maritime Data Space and Public Key Infrastructure

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Abstract

This paper presents the results from two research projects, both related to maritime information exchange, namely Maritime Data Space (MDS) and Cyber Security in Merchant Shipping (CySiMS). The MDS, as a blueprint of the International Data Spaces Association Architecture (IDSA), provides an ecosystem where data and information can be transferred efficiently between maritime stakeholders, maintaining the data owners' rights towards data governance. The CySiMS-project provides a Public Key Infrastructure, enabling safe, secure and trustworthy information exchange mechanisms. When combined, the two projects provide a complete solution for secure, trustworthy and efficient information exchange between stakeholders in the maritime industry.

1. Introduction

Increasing digitalization in the maritime business is one manifestation of the fourth major technology change in the sector after the steam engine around 1800, the diesel engine around 1910 and computers in the 1970s. We call this new major change for Shipping 4.0, *Rødseth (2016*), as it is closely aligned with Industrie 4.0, now changing production industry on land. Shipping 4.0 includes increasing integration of physical systems with their control computers ("Cyber-physical systems"), improved connectivity on the ship and between ship and land ("Internet of things at sea", "Internet of services at sea"), advanced data analytics and other elements. In short, pervasive use of digital information is a key element.

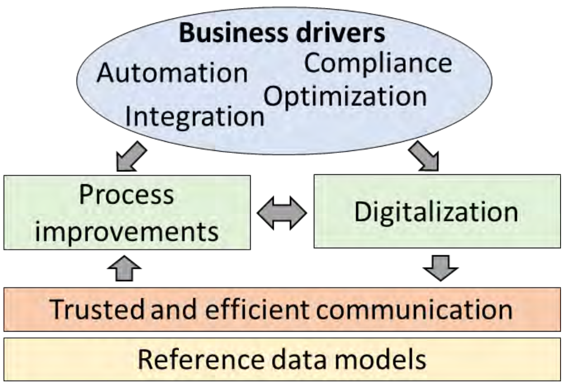

Fig.1: Drivers for Shipping 4.0

A simplified diagram showing some of the forces that are driving this process is included in Fig.1. New business drivers, like increased automation onboard and between ship and ports, optimization of voyages, just-in-time arrivals and ship systems, compliance to regulatory reporting and documentation requirements, and increased integration in the maritime domain, are all dependent on increased digitalization as well as process improvements. Process improvements are already taking place in all parts of the maritime business, but these are not the main theme of this paper. Digitalization requires data transport protocols that must work over a wide range of operational segments, including authorities, ship transport operations, port operations, international trade and so on. Until recently, this has been realized with a number of different data transport protocols, typically developed for each operational segment individually. The protocols have been based on "push" mechanisms where the client party, e.g. the ship, sends information to the service providing parties that need the information. Authentication, integrity and confidentiality (e.g. for privacy) are often implemented by common cryptographic mechanisms, although with some adaptations to the international shipping environment, *Rødseth et al. (2020b*).

In 2020, a significant step was taken by IMO and some of the main international standardization organizations in establishing the IMO Reference Data Model (IRDM), *Rødseth et al (2020a)*. This enables ship to shore interoperability between different protocol standards used in trade, ship operations and authority reporting, and work is under way to include more ship to shore operations in the model. So far, this has been used to implement digital communications between maritime single windows (MSW) and ships, but there is also work on ship route exchanges, *IEC (2020),* and ship automation data, *ISO (2018),* that may also be included in the reference model.

To provide a more flexible communication architecture, while continuing to observe the special requirements in the maritime domain, the MDS and CySiMS projects have developed new and improved mechanisms for digital communication between ships and shore. This includes the possibility to make use of reference data models like IRDM, a new "pull" type data exchange mechanism and a digital trust framework.

2. The need for new data exchanges in shipping

Ongoing work in IMO, ISO and IEC, as reported on in section 1, has already provided a platform for more seamless and automated information exchanges in the maritime sector. However, the communication infrastructure is quite complex. Fig.2 shows some of the actors and main communication possibilities, i.e. mobile data or satellite and the emerging VHF Data Exchange System – VDES, which is currently being developed by ITU, IALA and others. This is a higher capacity version of the Automatic Identification System (AIS) VHF data exchanges, *Bauk (2019)*. In addition, there are also possibilities for communication between the shore parties via conventional land-based internet.

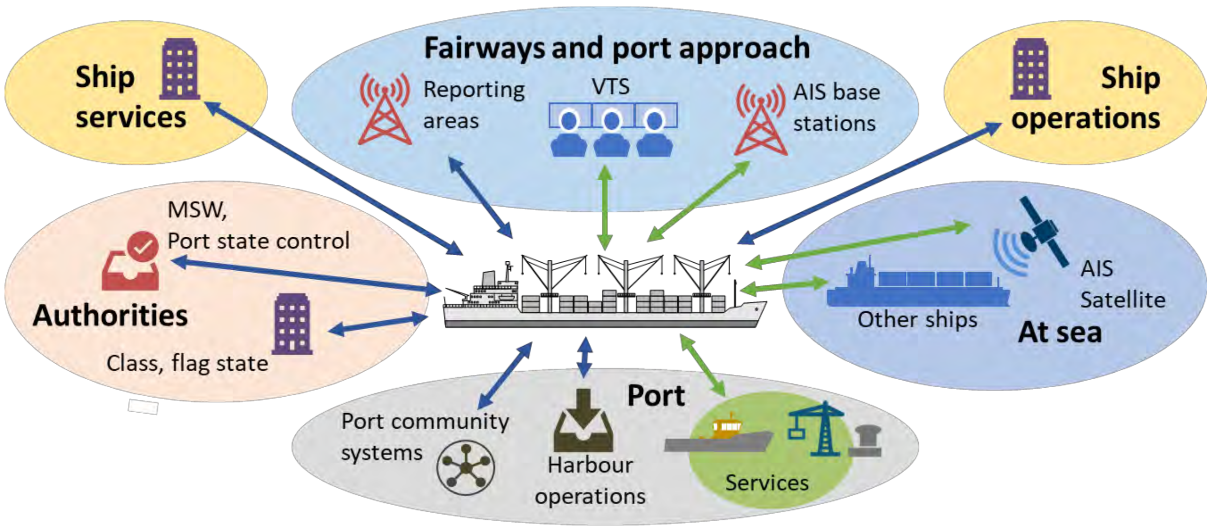

Fig.2: Parts of the maritime communication infrastructure

So far, developments have focused on push type data transfers between ship and shore, but there are important reasons why this should be extended to other forms of communication:

- Ships generally only have access to low bandwidth and costly communication when at sea. Thus, there is an argument for minimizing ship-shore communication and rather use land-based information sources when possible. Much of the information about the ship will also be available from the ship manager, owner, or charterer or from flag state or class authorities.

- The main cost-free communication channel for ship today is the very limited AIS system that can be used by shore base stations to detect when ships enter certain geographic areas. AIS also allows very small data messages to be transmitted in "Application Specific Messages" (ASM), and VDES when it becomes available, will increase this capacity significantly, but still far from typical satellite or mobile data capacities. This makes it interesting to trigger data transfers by AIS or VDES, e.g. as a form of geofencing, and use this to get more information from other land-based sources.

- There is an increasing interest in using different types of performance data from ships and their systems to benchmark against similar ships and to optimize or measure relative performance. Information from technical systems onboard can also be used in maintenance scenarios to get better statistics on failure rates and maintenance requirements. The data should still be controlled by the ship owner but needs to be made available to third parties.

A more efficient system for ship-shore communication is illustrated in Fig.3. Here, the ship mainly communicates with its shore operations office, e.g. ship management, owner and/or charterer. This will typically be sending periodic technical and operational reports and receiving voyage or port instructions. A service provider handling mandatory ship reporting for port calls could then use an AIS trigger to pull data from the respective shore operations offices. Another, e.g. engine performance analysis service provider, could get data from different operations offices to benchmark engine performance under different operational regimes and returning guidance to the ship operators. The latter service providers could also in principle pull additional information from other sources, such as the reporting authority.

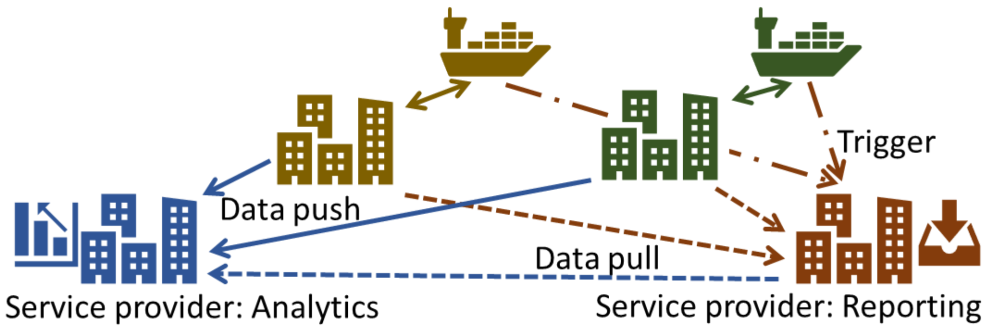

Fig.3: A better system for communication between ship and shore

To make this system work, the following components are needed:

- A common information model or a reference data model such as the IRDM. This makes it possible to collect data from different operational domains and give them semantic meaning in the relevant data usage domain, such as reporting or analytics.

- Mechanisms that can provide safe and secure data pull functionality in additional to the already existing protocols for data push.

- Mechanisms that can enforce data ownership and information security, independent of where the data is located, e.g. to allow the analytics service to pull data from the reporting service, without enabling other parties to access this information without proper authorization.

These are the mechanisms that are provided by MDS and CySiMS. In the following we will present both projects, their results and proof of how these results enable secure, trustworthy and efficient information exchange in the maritime industry. This through a selected set of business cases from the MDS-project where the CySiMS PKI is utilized to provide the sufficient level of security and trustworthiness.

3. The CySiMS PKI

The goal of a Public Key Infrastructure (PKI) is to enable secure, convenient, and efficient distribution of public keys using digital certificates. The CySiMS PKI has been designed based on the research documented in *Bernsmed et al. (2016)* which outlines a method to secure ship-to-ship and ship-to-shore communication using private keys, public key certificates and elliptic curve cryptography. The PKI has been implemented and deployed using a three-level trust hierarchy in which the top-level Root Certificate Authority (CA) and the Intermediate CA is operated by the Norwegian Maritime Authority. Public key certificates are issued to the PKI units of the end entities, i.e., the actors that need to communicate securely.

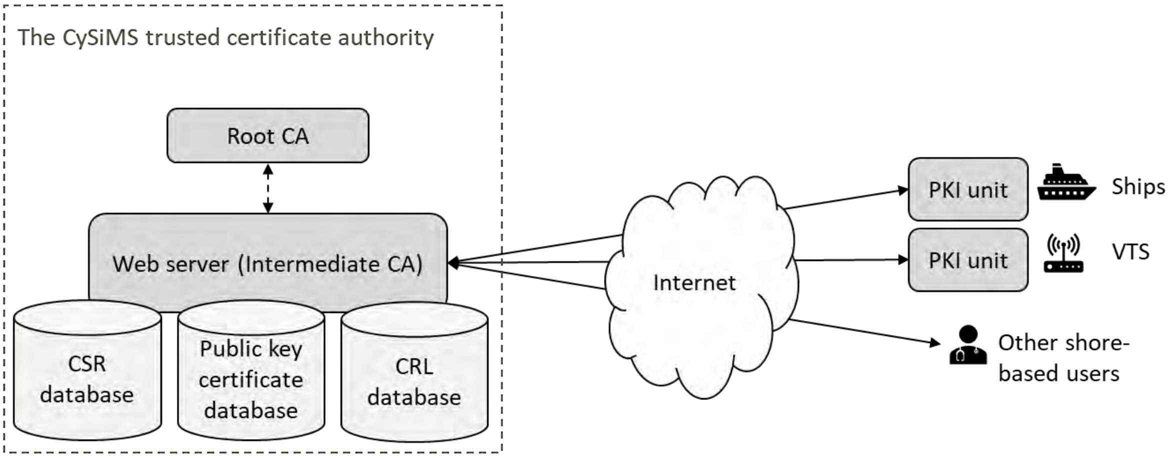

Fig.4: The CySiMS PKI

Fig.4 shows an overview over the main concepts. The CySiMS trusted certificate authority is accessible through a web server, which receives Certificate Signing Requests (CSRs) from the end entities: (ships, Vessel Traffic Services (VTS) and other types of shore-based users) and make the public key certificates available for download. The web server can also be used to distribute Certificate Revocation Lists (CRLs), which contain lists of the certificates that have been revoked.

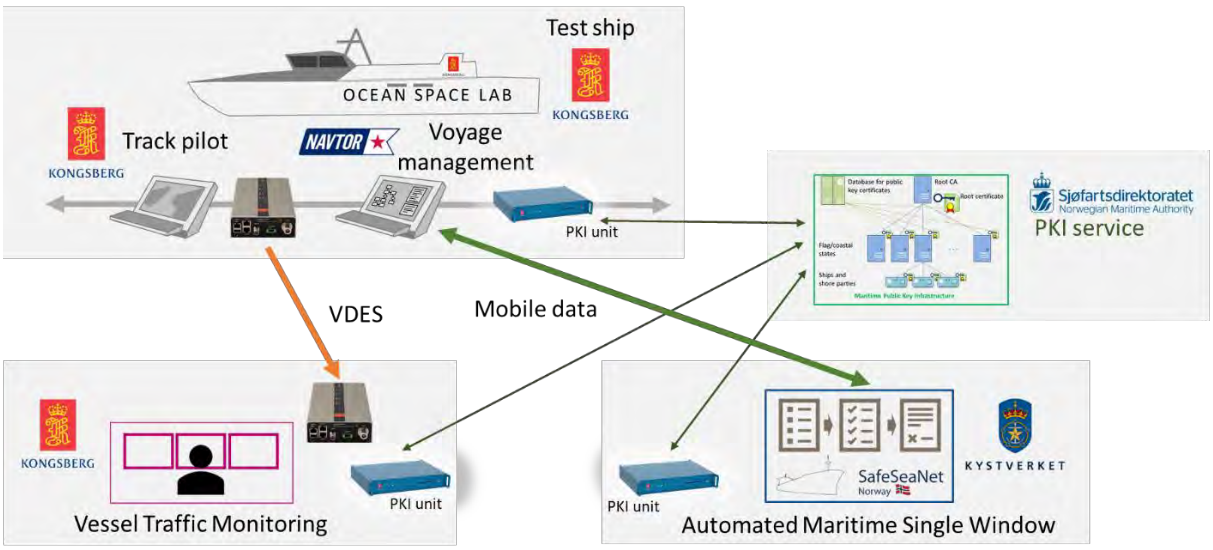

Fig.5: Actual CySiMS PKI-setup

PKI units are installed as part of the communication infrastructure of the end entities and are designed to be tamper resistant. This enables a secure storage of each entity's private key and a trusted device for performing cryptographic operations, such as signing, hashing, encryption and verification. The PKI units offer these services to the communication technology onboard, so that for instance a VDES radio can invoke it to digitally sign a message before transmitting it. The PKI units also provide a set of services for storing and retrieving public certificates when ships are offline. Shore-based users have the possibility of using a dedicated PKI unit, or they may use regular computers that follow the same specifications for managing the PKI.

4. The Maritime Data Space

The innovation project Maritime Data Space (MDS) has developed a federated ecosystem for secure, efficient, and trusted exchange and sharing of ship related data among trusted stakeholders on ship and shore. The core technology and business aspects of MDS is based on the reference architecture and guidelines promoted by the International Data Spaces Association (IDSA). IDSA is a coalition of more than 120 member companies from various industry sectors in 20 countries that aims at providing a global standard for data spaces internationally, https://internationaldataspaces.org/.

The IDSA Reference Architecture Model, https://internationaldataspaces.org/download/16630/, uses a five-layer structure expressing various stakeholders' concerns at different levels of detail. In this context, MDS will be defined as an implementation of the Reference Architecture Model (RAM). RAM is structured according to the following layers:

1) The Business Layer specifies the different roles of the participants, including activities and interactions related to each of these roles.
2) The Functional Layer defines the functional requirements of the data space.
3) The Process Layer specifies the interactions between different components of the data space.
4) The Information Layer describes the static and dynamic aspects of participants, technology components, and data offerings.
5) The System Layer describes implementation of technology components.

In addition to the five dimensions listed above, RAM includes three perspectives that need to be implemented across all five layers: Security, Certification, and Governance.

Core participants of a data space can be any organization that owns, provides, or consumes data:

- A Data Owner will define Data Usage Policies and provides access to data.
- Usually, the Data Owner automatically takes on the role as the Data Provider as well. The Data Provider makes data available to be shared between a Data Owner and a Data Consumer.
- The Data Consumer receives data from a Data Provider. A Data Consumer can connect to a Data Provider directly or via the Broker Service Provider.
- The Data User has the legal right to use the data of a Data Owner as specified by the usage policies. In many cases, the Data User and the Data Consumer roles are assumed by the same participant.

Intermediary roles establish trust and provide metadata and data catalogue functionality. The intermediary roles include the Identity Provider, the Broker Service Provider, and the Clearing House:

- The Identity Provider creates, maintains, manages, and validates identity information of participants in the data space. The Identity Provider consists of a Certificate Authority that manages and issues digital certificates to data space participants.
- The Broker Service Provider is a centralized role that stores information about participants and their data offerings. The Broker Service Provider is not involved in the actual data exchange process.

- The Clearing House provides clearing and settlement services for financial and data exchange transactions, and logs activities related to data exchange. Both the Data Provider and the Data Consumer confirm the data transfer by logging details of the transaction, and the transaction can then be billed. Furthermore, the information can also be used to resolve conflicts related to repudiation.

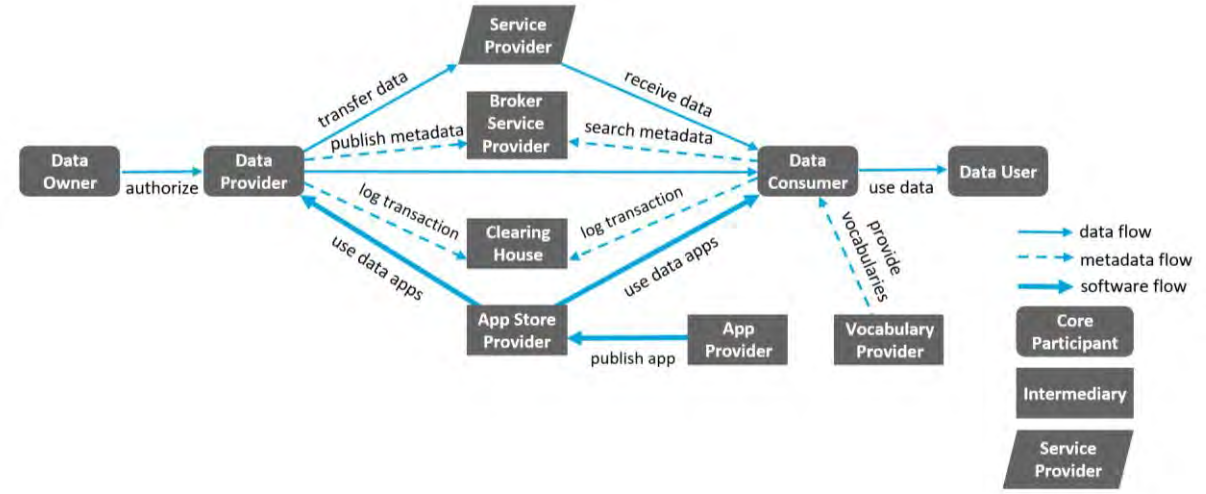

Fig.6: Roles and interactions as defined by the IDSA Reference Architecture Model

5. How the MDS and CySiMS PKI enable secure, trustworthy and efficient information exchange

The MDS framework architecture and the CySiMS PKI have both been validated through a set of business cases, represented by key players in the maritime domain such as governmental bodies (Norwegian Maritime Authority and Norwegian Coastal Administration and DNV acting as accredited verifier for EU), ship operations (Wilhelmsen Ship Management) and service providers (NAVTOR and Neuron Solutions). The validation consisted of a technical assessment, a functional assessment, and an administrative assessment. Below we present these business cases.

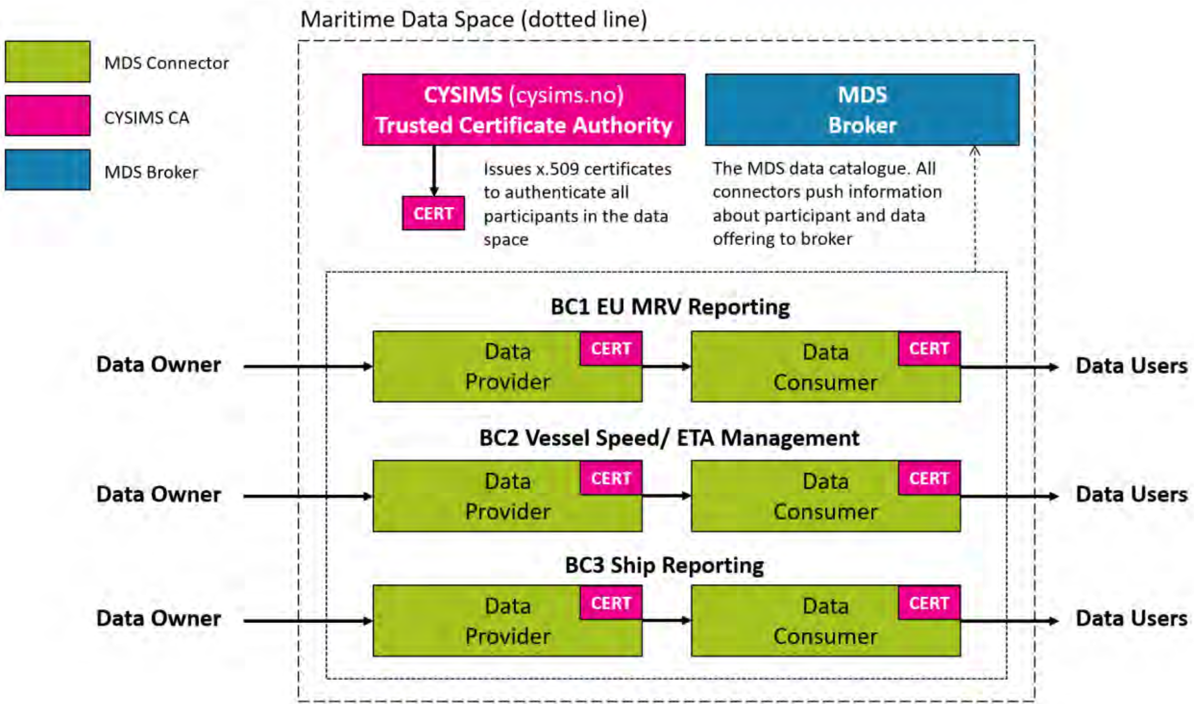

Fig.7: MDS Architecture

5.1. Automatic MRV reporting from Wilhelmsen Ship Management (WSM) to DNV

The EU MRV (Monitoring Reporting and Verification) regulation states that all ships above 5000 GT (regardless of flag) sailing to or from European ports must submit an emissions report to an accredited verifier for verification and later submission to the EU.

Through the MDS, ships under management by WSM submit the required data (through a generic data capture tool provided by Neuron Solutions) to Veracity by DNV, https://www.veracity.com/. No manual processing or reporting is required as the MRV requirements are implemented in Neuron Solutions' MDS-connector, hereunder the mapping of data tags between WSM and DNV and the logic needed to ensure that emissions data are correctly linked to the transport work (cargo carried and distance sailed). Veracity by DNV thereafter ensures access to the data to DNV, acting as accredited verifier by EU. Any deviations in the emissions reports are identified by DNV and Wilhelmsen Ship Management is immediately notified to ensure a timely intervention to mediate the identified deviation.

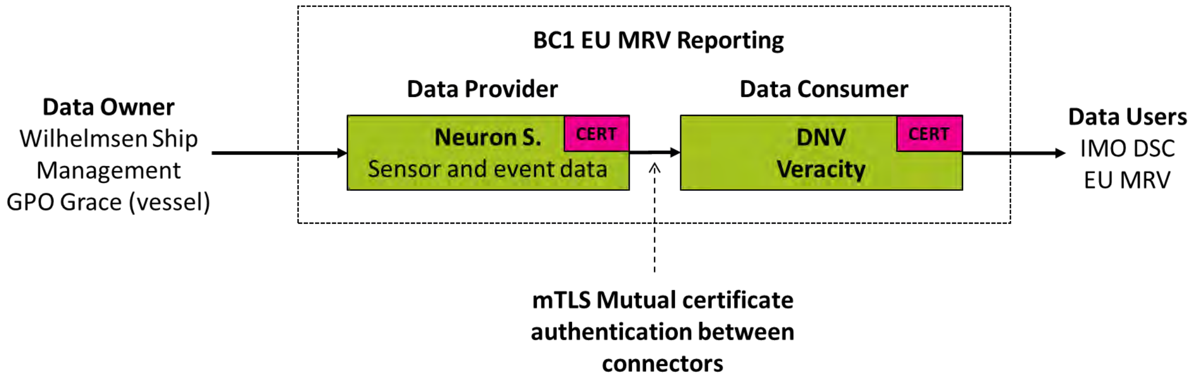

Fig.8: MRV reporting through the Maritime Data Space

MRV reporting through MDS ensures that no manual operations are needed to comply with the MRV regulation, hereby reducing administrative workload and increased efficiency in the verification process.

5.2. Data as an added value service – ETA management by Wilhelmsen Ship Management

ETA management is a prioritized HSEQ feature for WSM, ensuring high energy efficiency for the WSM ships through administrative measures as opposed to (and in addition to) pure Energy Efficiency Technologies.

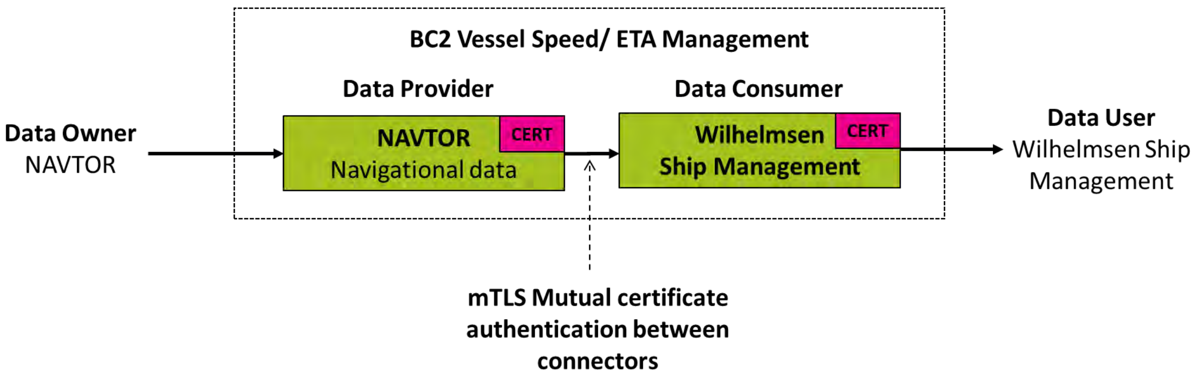

Fig.9: ETA management

NAVTOR, through their NavStation onboard WSM ships, contains the required data needed by the internal ETA management tools in WSM but external access to these data were initially not possible.

Through the MDS, data from the NavStation are transferred to WSM who are then able to analyse these in their internal ETA management tools, ensuring a much higher level of details, thereby increasing the value of the ETA management analysis.

Through the MDS, NAVTOR is able to create new value-added services to their existing and potential clients at a low-level threshold in terms of removing the need for proprietary APIs on both the provider and the client side.

5.3. Automatic MRS-reporting to the Norwegian Coastal Administration

Mandatory Ship Reporting, in the Norwegian Coastal Administration's case through the Maritime Single Window (SSN NO) is a reporting regime for ships entering Norwegian waters. In this business case, NAVTOR captures the required data from the ship through Neuron Solutions' MDS connector, processes the data and generates the required MRS message. A request for the PKI signature is sent to the PKI unit which signs the message and sends it back to NAVTOR for submission through the Norwegian Coastal Administration's Maritime Single Window. The Norwegian Coastal Administration verifies the signature using the PKI-unit and approves/rejects the message.

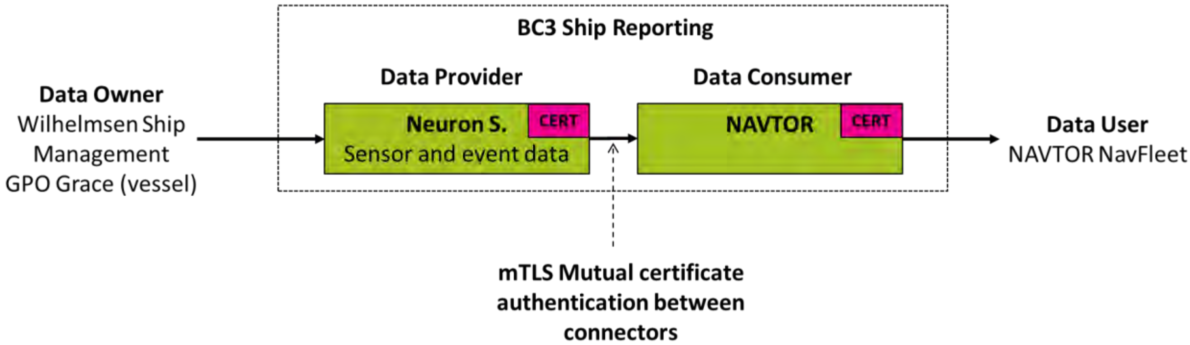

Fig.10: Automatic MRS-reporting (data capture)

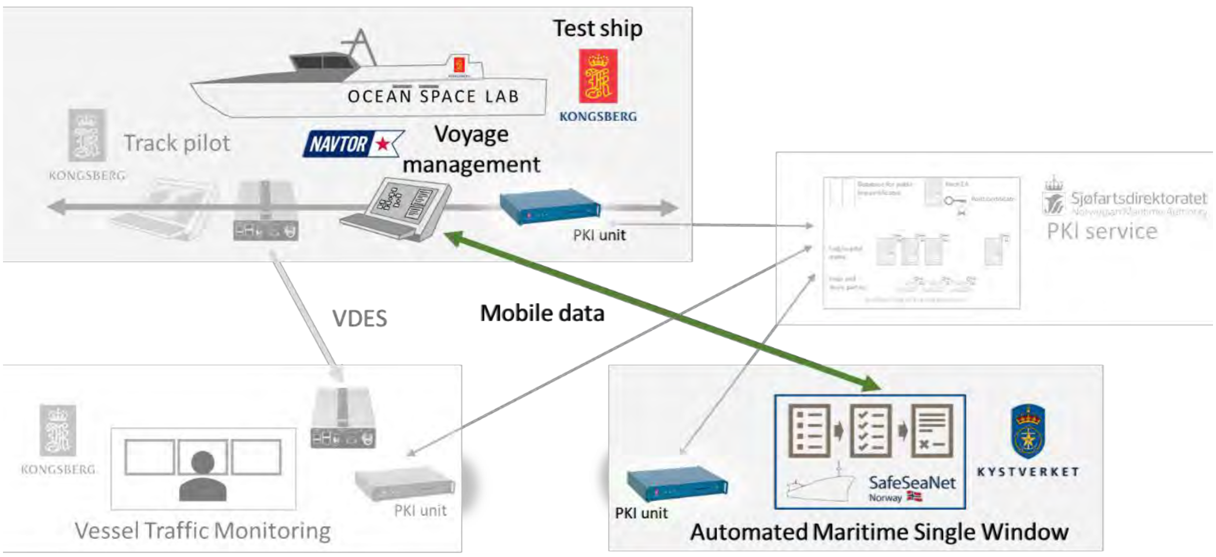

Fig.11: Automatic MRS-reporting (create and verify signature)

Through the MDS, in combination with the CySiMS PKI solution, NAVTOR is able to capture required data from the ship and sign the MRS message. The Norwegian Coastal Administration is able to verify the sender of the MRS.

6. Discussion and Conclusion

This paper presents the results from two research projects, both related to maritime information exchange, namely Maritime Data Space (MDS) and Cyber Security in Merchant Shipping (CySiMS). When combined, the two projects provide a complete solution for secure, trustworthy and efficient information exchange between stakeholders in the maritime industry.

Trustworthy and secure as the CySiMS PKI solution ensures that both sender and receiver is authenticated, and the content may be signed/encrypted at the sender's side and verified/decrypted at the receiver's side. Non-repudiation is supported through the introduction of the intermediate role of the Clearing House which logs each information exchange. Efficient as the Maritime Data Space represents an open architecture where proprietary APIs are replaced by generic connectors. In addition, the principle of data governance is supported through the Maritime Data Space's support of the different roles which participants can assume, including activities and interactions related to each of these roles, on basis of who owns the data, who processes the data and who uses the data.

The business cases presented document how the CySiMS PKI and the Maritime Data Space architecture framework are implemented and utilized to support the industry participants' needs for secure, trustworthy and efficient information exchanges. This to substantiate the wave of digitalization on which the maritime industry currently is on. The move from digitization, through digitalization towards digital transformation, rely on actual implementation of solutions such as the Maritime Data Space and the CySiMS PKI. The industry players are then able to see how their business and business relations can develop and thrive on basis of actual available solutions and not merely the use of digitalization as a buzzword.

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Deming Cycle Enabled: A Digital Twin for Ship Production

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Abstract

This paper presents the current status of the R&D project ProProS undertaken by the shipyard Fr. Lürssen, university RWTH Aachen and PROSTEP. The goal of the project is to develop methodology and tools for efficient and near-time production planning for typical one-of-a-kind ship production.

1. Introduction

A common problem in the production of shipbuilding or offshore structures is to plan the production appropriately. The shipbuilding production process is often planned only roughly in weekly or even monthly slices, with detailed planning skipped completely or done by foremen for their team's purpose. Feedback on problems in either delivery or production is not available promptly. Late time changes demanded by ship owners impose additional problems. As a result, the visibility of the actual status is often poor. Thus, acute problems are not detected in time making mitigation actions more expensive in terms of time or expenses than necessary.

The research project ProProS aims on helping the shipbuilding industry to perform better planning of the manufacturing process and thus reduce time and effort. The base idea is to enable planners to run a complete Deming, Fig.1., process over and over again with reasonable effort. Planning the production once in terms of schedule and needed resources is common practice, but permanently updating the planning taking changes into account is rarely done.

This replanning is currently rather difficult, as few if any tools enable this for prototype production like in the shipbuilding industry. Only if the production planners are aware of the product itself, production processes to run, available resources, and the production status they can perform the 'Check' action and consequently perform correct planning for the next period (shift/day/week). This requires both retrieving information from several sources in a yard as well as preparing this to perform the 'Check', 'Act', and 'Plan' action. This paper shows the current status of the research projects both in terms of developed processes as well as an IT tool.

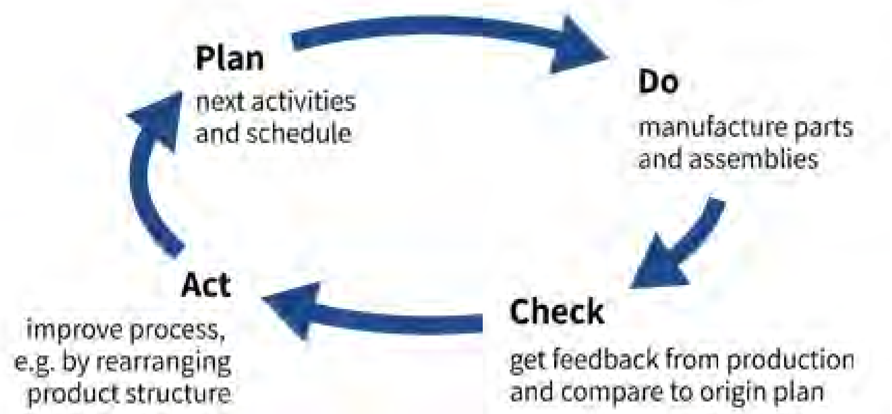

Fig.1: The Deming Cycle, *Deming* (1986)

2. Production Planning

Every shipyard needs to somehow plan how a new vessel is going to be produced. Many information items are relevant for this planning process, most notably the assembly structure of the vessel itself, production activities to perform, available manufacturing resources, and last but not least restrictions in terms of schedule and money. Similar to the design process of a vessel, this planning process is not only run once but needs to be performed on several stages of the vessel's lifecycle with different methods and reliability of available data. The planning is based on the current status of the design and production process plus estimation of real production times. The reliability of the estimations depends on the chosen method as well as on the underlying data. But even if a yard has perfect control over its processes and thus totally reliable estimates, external factors like purchase status or changes demanded by a customer necessitate running a new Deming cycle to take these changes into account.

2.1. Stages and Methodologies

Production planning is done at different stages of the vessel's lifecycle, Fig.2. Even before signing the contract, some preliminary production planning is needed to figure out a realistic delivery date. Only a few basic parameters and the general arrangement plan are available at this time, therefore the preliminary planning must use expert judgement or analogue estimation based on historical data of previous vessels, *PMI (2017)*, chapter 6.4). The reliability of this estimation is driven by the amount, accuracy, and applicability of historic knowledge. This is quite a risk, as the delivery date fixed in the contract relies on the estimated production times. Even if a yard is meticulously collecting data for future usage, a new ship type or production method may render this information useless for the vessel to estimate.

During the design phase, the amount and reliability of input data increase permanently. Information like number, type, weight, and volume of sections is now available as input for a parametric estimation of needed resources and times. This results in a better fidelity compared to analogue estimation and is available 6-12 months ahead of production start. The resulting data is needed to allocated building places and docks as well start purchasing items with longer delivery time, so they are available in time for assembly.

In the late design phase, design is ready down to plates and stiffeners, supporting a bottom-up methodology offering the most accurate estimate. Depending on the ship size, planning horizon, and granularity of the estimation we need to handle millions of parts with their production or delivery status as input for the planning. As this is nearly impossible without dedicated tools support, this is the focus of the research project.

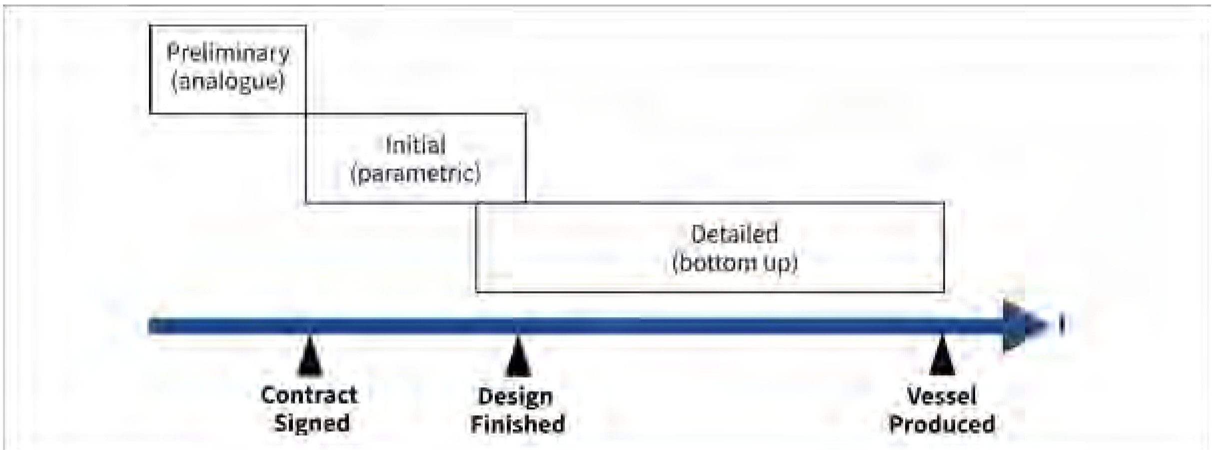

Fig.2: Vessel lifecycle and planning stages

2.2. Schedule Management

To know, which manufacturing activities are run at what time, we need to perform schedule management. This typically requires the following steps, *PMI (2017),* chapter 6:

1. Define Activities
2. Sequence Activities
3. Estimate Durations
4. Develop Schedule

The expected outcome is scheduled manufacturing activities and, as a by-product, the needed resources. When developing the schedule, one has to consider restrictions e.g. due to availability of raw material, resources and last but not least the vessels delivery data.

The first step in the planning is to define the activities needed to produce a vessel. Most yards have some kind of activity template, which reflect their production methodology and capabilities. An example is found in Fig.3, it contains an example workflow as BPMN diagram found on many yards. The process consists of activities and subprocesses (groups of activities), connected to represent the overall process by the arrows.

In this template the production starts with part fabrication, resulting in plates and stiffeners. The activities needed for this like loading a raw plate on the burning machine to potential rolling or bending are found in the subprocesses for plate or profile production. Whether this is needed as activity depends on the design of the part. These parts are then assembled either on an automated panel line or a manual workstation to assemble like the deck girder or deck panel. Those assemblies are then moved to section manufacturing and, finally, the sections are moved to the dock to erect the ship.

It is important to understand, that this diagram does not represent the individual actions needed to produce the ship. The diagram represents an activity template, which is then applied on the vessels as a planned product structure, resulting in the activities themselves. An example is contained in Fig.4. On the left you find an example as planned product structure for a deck panel. It contains the deck plate assembly and three girder assemblies.

The activity template is then applied to the as planned structure resulting in the activity network diagram on the right-hand side. This contains one activity on the panel line for the deck plate assembly and three manual activities to assembly the deck girders. Those four assemblies are then used as input for the final activity to create the deck panel. The inner activities of the "manual" process from the template is shown as an example for girder #1.

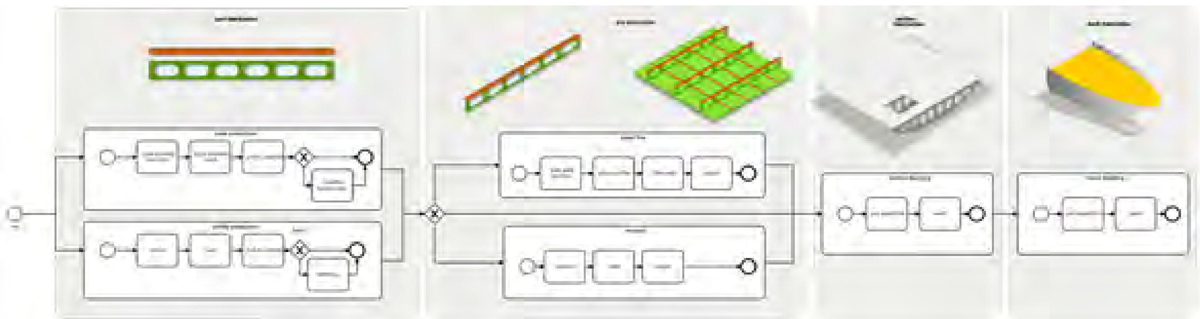

Fig.3: Example activity template

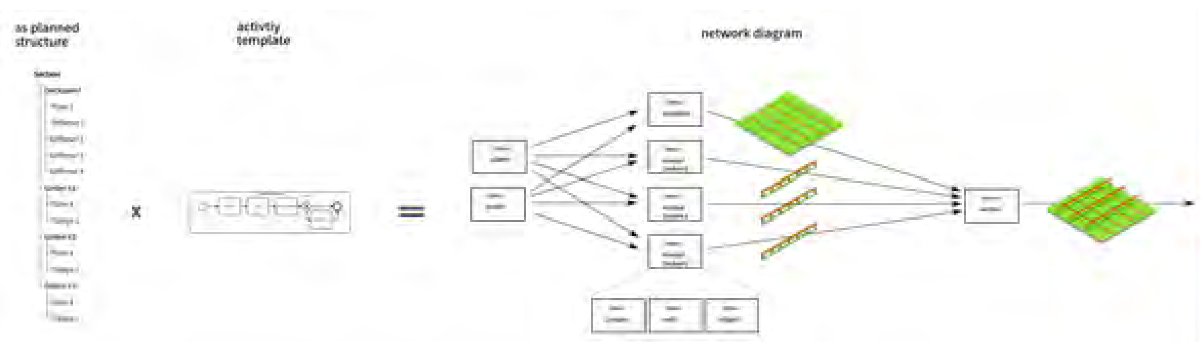

Fig.4: Apply activity template on an as planned structure to create activity network

After the activity network is created, we need to potentially apply the sequencing to enforce a certain order. As we focus on the planning aspect with respect to the overall time, sequencing is rarely needed on panel or section level. It is needed though to create the sections in the right order according to the yards preferred erection order in the dock.

Using the activities and information on the related parts, it is now possible to estimate the durations of the activities. The estimates are created using a bottom-up approach, e.g. the duration of assembling the deck girder is based on the three sub-activities “preparing”, “welding”, and “adjusting”. As seen in Fig.5, the activities are related after creation from the templates. This does not only include reference to the parts used as input or output (so we could access the welding length of the flange), but also related resources like personal, location, or machine. Based on this information it is now possible to estimate the duration e.g. welding the flange to the girder plate with simple formulas, but achieving good results.

The final step is then to develop the schedule based on the network using the precalculated durations. This step needs some additional constraints to get a valid solution. This includes the schedule of available resources, which is easy concerning to locations which are available 24/7. It gets more complicated when taking resource groups like personal into account as these are depends on working days, the number of externally purchased welders etc.

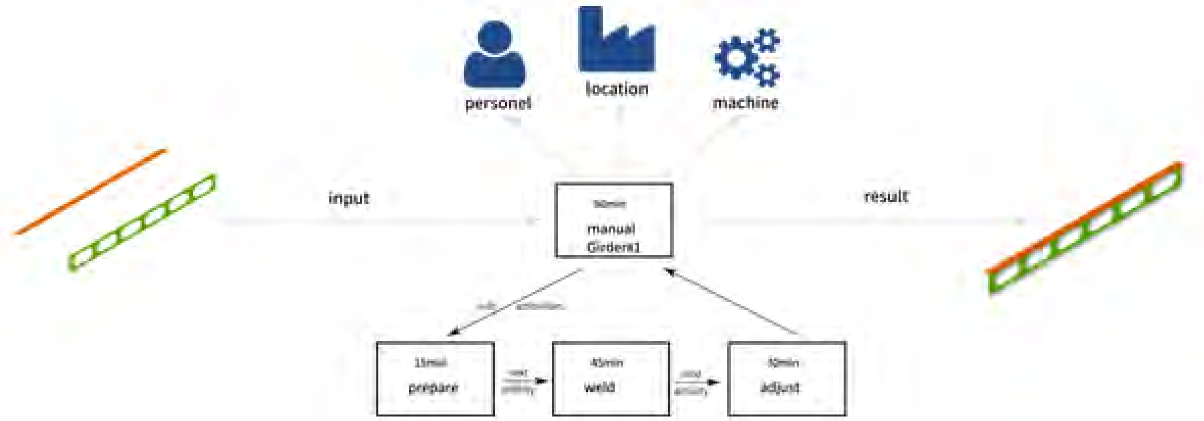

Fig.5: Information related to activities

2.3 Information Needs

All four phases of the Deming cycle have different information needs to run the associated business logic. In this research project, we concentrate solely on the planning purpose, information needed for another purpose (e.g. drawings, NC data) are not investigated. All steps need the output of the previous step as an input, Table I, they provide new information either by gathering information from external sources and then applying some business logic purely in a manual or automated manner.

Table I: Information Needs and Provision for Planning Purpose

Deming Step	Needs	Provided	Data Source
Plan	Activities to run Scheduling parameters Constraints	Scheduled Activities, Resources, Locations, Raw Material	
Do	Scheduled Activities, Re-sources, Locations, Raw Material, …	Feedback on Activities (happened, failed, needed duration) Timing information	Shopfloor
Check	Scheduled Activities, Resources, Locations, Raw Material Feedback on Activities	Status	
Act	Status Product Structure Timing information	Activities to run Scheduling parameters Constraints	Design Purchasing Hiring Investigating

Both the ‘Do’ and ‘Act’ planning steps rely on getting information from yard departments to provide the needed information. In the ‘Do’ step, it is necessary to get information from the shop floor, about the status of the planned activities. If this is not available in the appropriate granularity and promptly, further planning steps will not work. The ‘Plan’ and ‘Check’ step are solely based on information from previous steps and apply some business logic, to create the needed output.

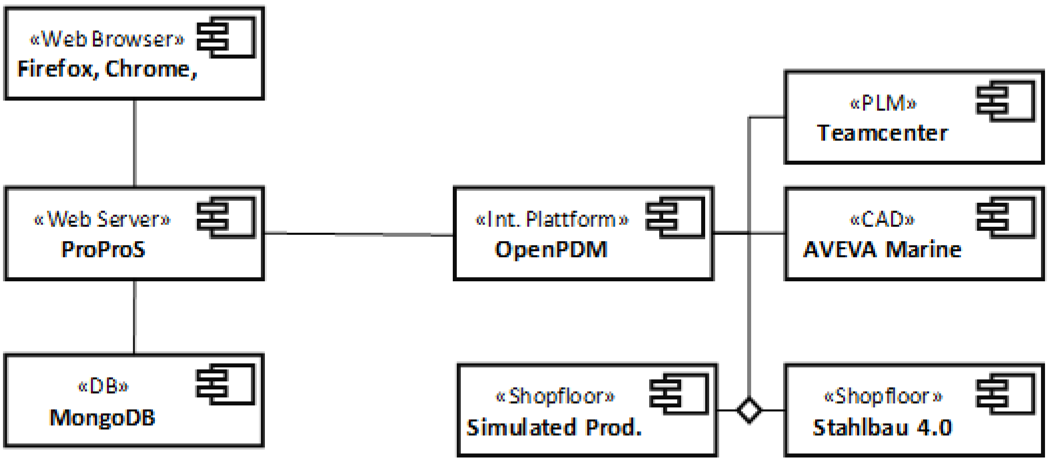

Fig.6: ProProS deployment diagram

3. ProProS Demonstrator

Implementing these ideas in a real IT tool is crucial to check the applicability for real production processes. Therefore, we started implementing a software demonstrator in January 2021. As seen in Fig.6, the demonstrator is implemented as a web application, providing a browser-based user interface. The server itself uses PROSTEP’s low-code framework, allowing us to generate the code for data management and remote access from one description. Consequently, we could concentrate on the code for the user interface and the business logic.

3.1. Data Model

As discussed before, the ProProS data model must be able to reflect the as planned product structure, manufacturing activities, needed resources as well as feedback coming from the shop floor. When designing the data model, we followed some basic ideas:

- Concentration. There are no fields or classes which are not related to the production planning process. We do not want to replicate data or functionality which is already available in e.g. Teamcenter or AVEVA Marine and not needed for planning purposes.
- Divide. As seen in Figure 7, the data model is broken down into domain-specific areas. Given a schedule is needed on an assembly, this information is not added as a field to the assembly, but as a separate object containing that information. This reduces interdependence between e.g. the technical domain (plate) and planning domain (assembly activity).
- Imitation. There are proven data models for sub-domains like project management or organisational data. Instead of reinventing the wheel we follow well-known and documented data models like X.500 (X.520, X.521, RfC 2798), *RFC (2000)*, or AP242 BOM (ISO-10303/AP242 BOM), *ISO (2014)*.
- Categorisation. Whenever there are multiple shapes of the same object, we use one class plus a categorization. E.g. there is only one class for assemblies, but an additional categorisation distinguishing panels from sections.
- Weak vs. Strict. As the demonstrator already supports data from multiple sources, we need to find a balance between a completely hardcoded data model and a soft data model. A hardcoded data model uses dedicated fields and classes for all kind of information. It is maintainable with

a moderate effort, but at least in a research project, not all information needs are known in advance. Weak data models based e.g on the ubiquitous XML are JSON are easier to enhance, but then difficult to use, as information is simply missing. We use a middle way by attaching generic values items to contain information merely needed for reference purpose. They contain not only the value but also metadata about the type and unit of that information maintained in a catalogue.

3.2. Integration

Running the production planning as outlined in chapter 2 requires at least integration with the system used to design the as planned product structure as well as getting feedback for the current production status. As of June 2021, we already integrate with data from SIEMENS Teamcenter (used by Fr. Lürssen) as well as from AVEVA Marine to access reference data. This allows us to check functionalities both with reference data from a project partner as well as complete, publicly available demo ship.

The integration is using PROSTEPs integration framework OpenPDM Ship. This provides out of the box connectivity with standard PLM and ERP systems as well as integration with shipbuilding specific tools like AVEVA, CADMATIC, NAPA, ShipConstructor. In the next sprints, we will also add access to the shop floor system used at Fr. Lürssen yard. To enable testing the 'Check' step with different outcomes from the production, e.g. on time or delayed, we plan to add a Monte Carlo style simulated production to the test setup.

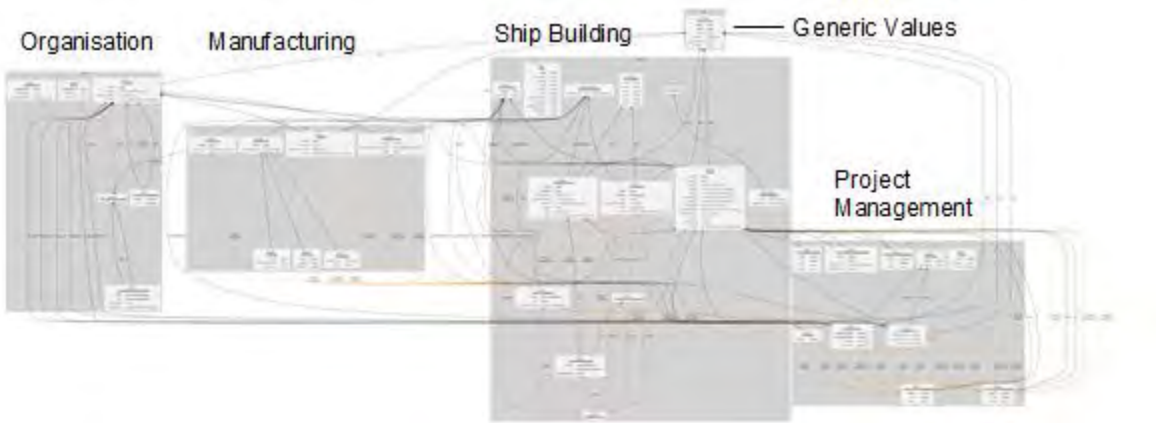

Fig.7: Data Model overview

3.3. Functionalities

Providing data storage and integrating with existing data is not enough, the ProProS demonstrator needs to provide some functionalities running on that data. As laid out in the second chapter, the main business functionalities are:

1. Applying the activity template
2. Editing planning constraints
3. Estimate activity durations
4. Calculate schedule
5. Calculate resource usage
6. Compare planned vs. as-is

The implementation focus is currently on the activity template mechanism and the duration estimation. As mentioned before, we use input from Teamcenter and AVEVA Marine, so we could check the implementation runs on a variety of data and not only one handcrafted set of demo data. We are now able to automatically calculate the activity network for an as planned structure, Fig.8. Implementation for the activity duration is currently running, preparation for schedule calculation has started as well.

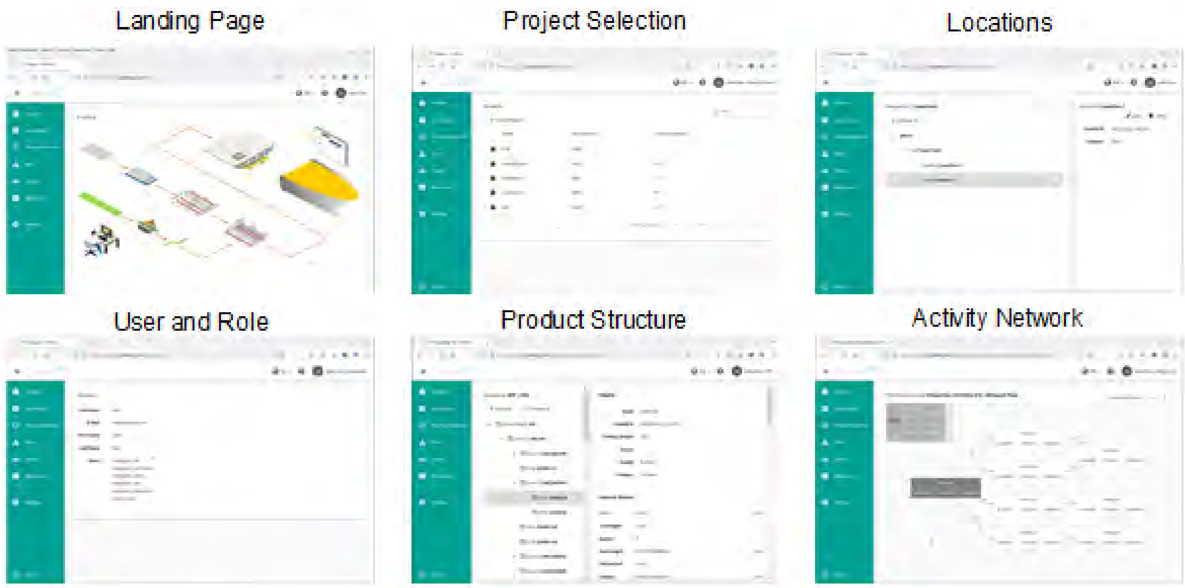

Fig.7: Samples from ProProS user interface

3.4. User Interface

Storing and processing data is no end in itself. The purpose of the ProProS demonstrator is to (re-) calculate the scheduling and later on display the status in the *Check* phase. This needs communication to human users, which is done by the web-frontend of the ProProS server. This web-frontend allows the user to perform basic setup task, as well as to run the functionalities described above and see their outcome.

The interface uses state-of-the-art technology like Angular, TypeScript programming and GraphQL communication on the browser platform. It also supports the role-based-access-control also found in the backend. This is used to reduce both the access to data and functionalities. It enables the administrator to prevent user to read or manipulate data they should not, e.g. an administrator vs. a planner role or project-based access roles.

4. Result and Outlook

The research project started in late 2019, the end is in late 2022. The complete workload is split into four work packages:

- WP1 Requirement Analysis. Analyse currently applied methodologies, available information, and requirements towards a better solution
- WP2 Enhance Methodology and Data Model. Identify better planning methodologies and supporting data model
- WP3 Implementation. Implement the solution as a proof of concept
- WP4 Validation. Validate the solution using real yard data.

Though the first two work packages had some impact due to COVID-19, we have finished WP1 and most of WP2 in time. The WP3 started on time and already made good progress to implement the demonstrator.

From the content side, we are also in good standing with the R&D project. The ideas we had when starting the project are approved by Fr. Lürssen's planning specialists in workshops and interviews. The implementation for 'Act' and 'Plan' functionalities in the ProProS demonstrator is going well. We expect the new shop floor system available by the end of Q2 2021, so we have real-world data available to also implement the 'Check' functionalities.

Acknowledgements

I would like to thank my PROSTEP colleagues Ulrike Lutz, Christina Strobel-Hoffman, Alim Kerimov, Jan Bitomsky and Nils Sonnenberg for working on this project as consultant or software developer. I further like to thank all colleagues from Fr. Lürssen and WZL who participate in the R&D project.

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The Need for an Updated Energy Decision Support System Framework when Retrofitting Ferries with Batteries - A Case Study

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Abstract

To embrace energy efficient operations and advanced energy management the concept of an updated Energy Decision Support System Framework is introduced. This case study is based on operational data from the ferry M/F Langeland with a 45-minute crossing time and relatively short port calls. The study shows that by supporting energy efficient operations, transparent charging plans and ensuring consistent fast berthing the battery capacity can be reduced significantly when retrofitting the ferry. The case study also indicates that unsupervised Machine Learning can be used to find optimization candidates.

1. Introduction

In Denmark there is a broad political agreement on achieving a 70% reduction in CO2 emissions by 2030, and by 2050 Denmark should be climate neutral. The 2030 goal is described in a climate program, https://en.kefm.dk/. The main sustainable energy sources in Denmark are wind and import of hydro power from Norway and Sweden. Solar power is also used, but it only covers less than 3% of electrical energy by 2020. The next step is Power2x energy. Denmark has decided to construct the world's first wind energy hub as an artificial island in the North Sea.

One of many areas in the 2030 program is the electrification of ferry operations. Domestic ferries contribute with a CO2 emission of 72.000 tons per year. There are multiple examples of fully battery powered ferries in shorter services with great success. In 2019 the newly build M/F Ellen, https://www.el-færgeprojekt.dk/, was put into operation. In 2022, the ferry M/F Grotte will follow, https://www.fanoelinjen.dk/.

The combination of cost-efficient operation, energy management, ensuring safety margins, and battery preservation will be a new operational topic when retrofitting existing ferries with batteries. *Mikkelsen et. al (2016)* described a model for evaluating energy efficient operations. This work can be extended to handle battery operations. It is also possible to generate charging plans to maximize energy efficiency, cost, and battery lifetime based on the works of *Mikkelsen (2013).*

A decade ago, LNG (Liquified Natural Gas) was an important energy source to be used in reducing emission from transport. Now there is a shift towards electrification after several successful installations of batteries in ferries. LNG is therefore no longer an attractive alternative fuel.

Hydrogen could also be an option without a carbon footprint. Today the infrastructure in Denmark is not mature and in place, but hydrogen is a central fuel in the power2x strategy laid out by the Danish Ministry of Climate, Energy and Utilities.

Retrofitting vessels with batteries requires electric propulsion and space for batteries. This will cause some ferries to be unapplicable for batteries, compared with new builds where hull design can be energy optimized and designed to contain the batteries.

The two sister ferries M/F Langeland and M/F Lolland are built in 2012 as diesel-electrical and they are sailing on the route between the port of Spodsbjerg on the island Langeland and Tårs on the island Lolland in Denmark. The ferry M/F Langeland depicted in Fig.1 has provided data for the case study described in section 3. The ferries are fulfilling their mission with regards to capacity and robustness, so it seems most obvious to retrofit them instead of making new builds. The two ferries were designed with void space for a later LNG conversion. This space can be used for an eventual Battery ESS (Energy storage system).

Fig.1: M/F Langeland

In this case study all power i.e. propulsion, auxiliary systems and heating (heat pumps) should be fully electrical with backup from the existing diesel generator sets. The batteries in focus are Li-ion types.

One of the ferry company's requirements in the retrofit project is to use the existing electrical infrastructure on-board the ferries. This will reduce the approval process. By leaving a number of the diesel generator-sets, a backup solution is also in place. Fig.2 shows the three most obvious charging options.

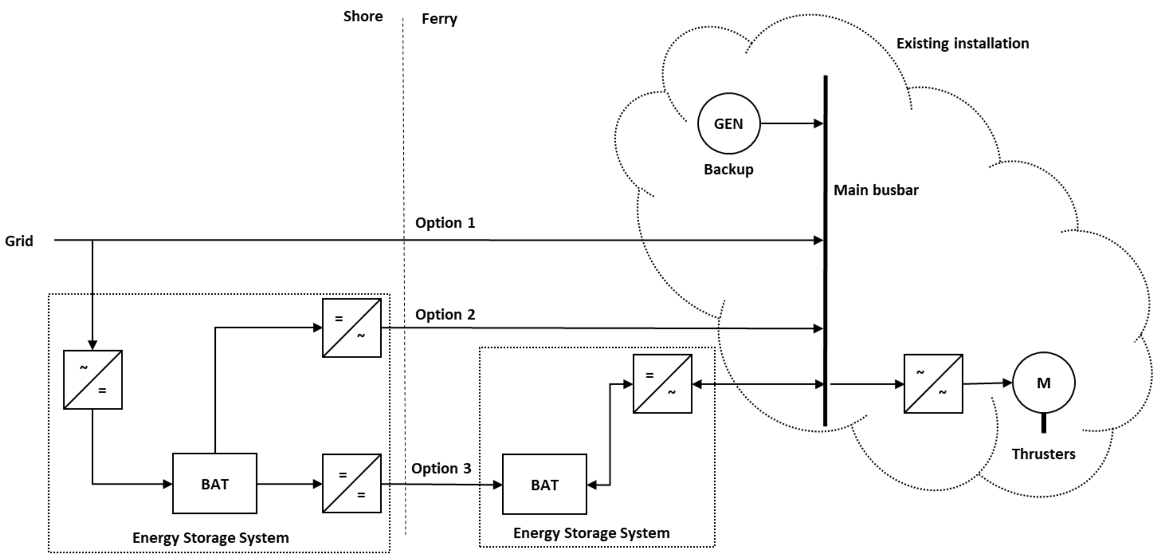

Fig.2: Electrical shore connection options

Option 1 requires a new high power grid connection, whereas option 2 and 3 can be installed using the current power lines in the two ports.

2. Updating model mode/state to battery operations

The mode/state model, Fig.3, was developed by *Mikkelsen et al. (2016)* for ferries, supply vessel or wind installation ships. It consists of four modes: 'Harbour', 'Maneuvering', 'Passage' and 'Offshore work'. Each mode contains a number of states as shown.

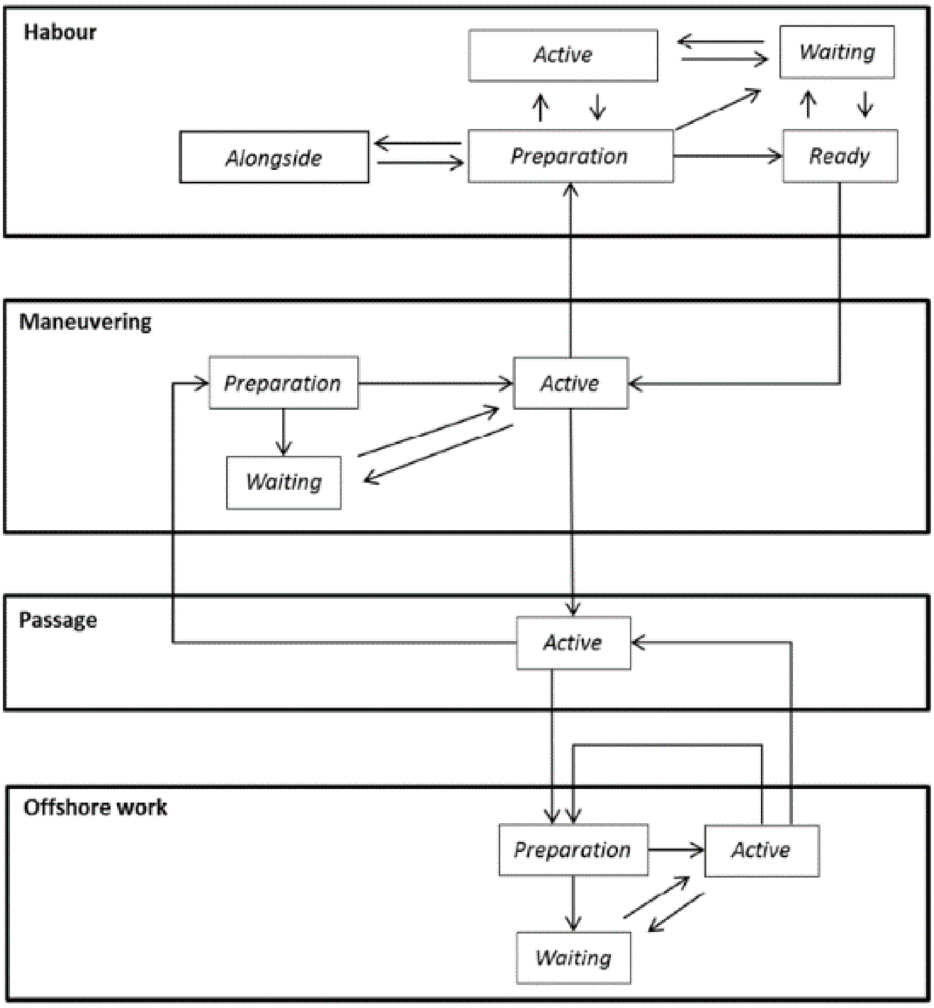

Fig.3: COMPIT 2016 *Mode/state* model

The model is updated as shown in Fig.4 to support advanced optimization algorithms and use of machine learning for ferries powered by batteries.

The following changes are made to model:

- 'Harbour mode' is reorganized and extended. The first state after berthing is now preparing for charging, this means electrically connecting the ferry to the onshore charging station. When the ferry is connected, the charging can start. Alongside is removed and instead the Not active state can be used at night without any operations.
- 'Maneuvering mode' is simplified as the waiting state not used and therefore removed. The berthing operation is still part of the 'maneuvering mode'.
- 'Passage mode' is unchanged.
- 'Offshore work mode' is removed, as it is not relevant.

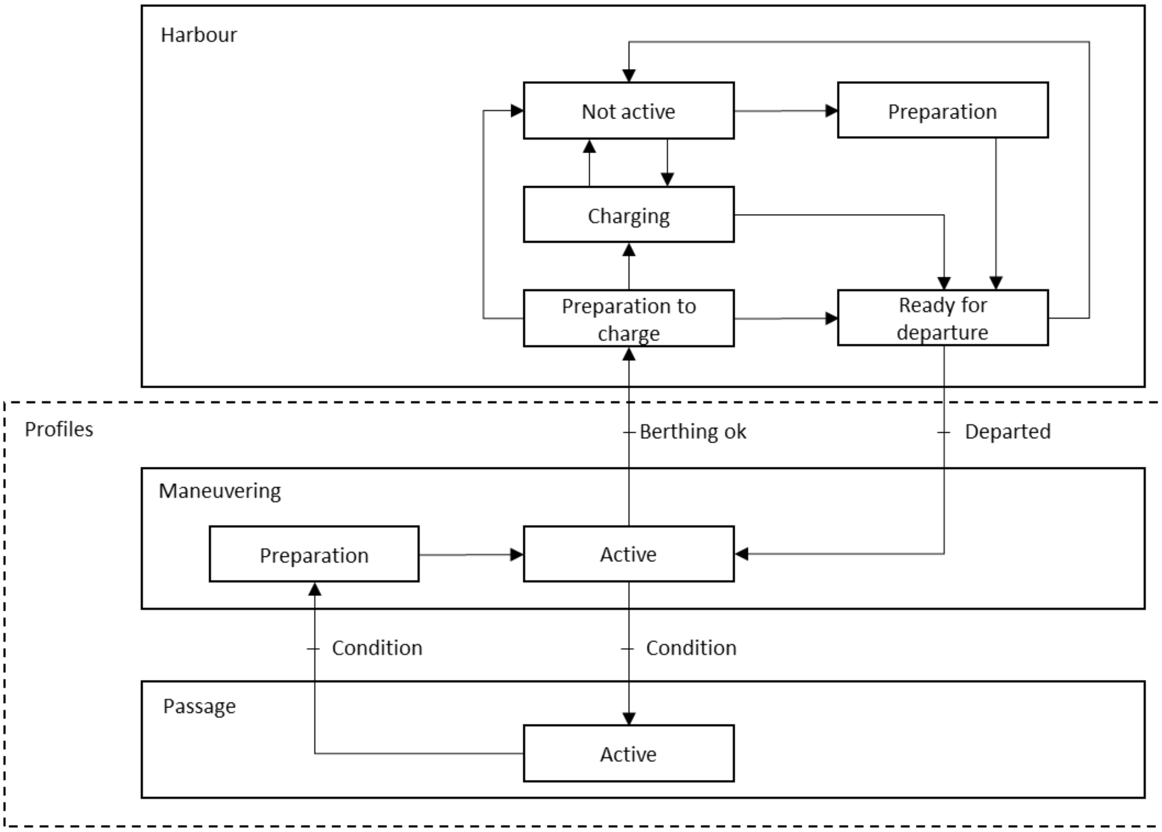

Fig.4: Ferry mode/state model

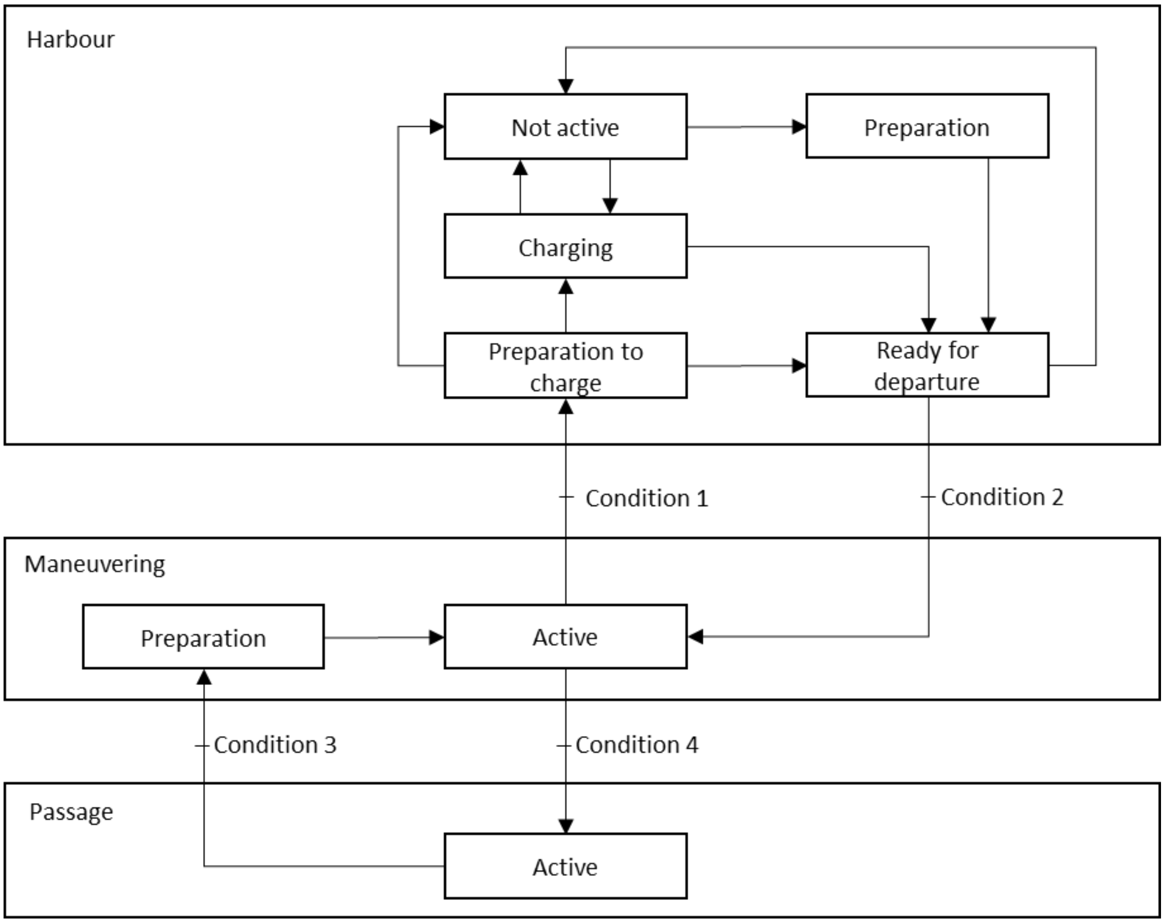

Fig.5: Ferry mode/state model with transitions

When the operational data is analysed, it can be important to identify trips with equal conditions e.g. longer routing due to traffic, weather, wind, current, power source (battery, hybrid or pure diesel), crew, etc. The extra information can be added as labels to the modes or states depending on the analyses.

As shown in Fig.5 the model can be more explicit by extending it with transition conditions to show what is required to change state e.g.

- Condition 1 = “berthing completed”
- Condition 2 = “departed”
- Condition 3 = “position A”
- Condition 4 = “position B”

3. Case study

The focus for this case study is to provide input to the framework proposed in section 4 which can support the initial decision when scoping the project, develop training programs and create battery charging plans, when the ferries are converted to battery operation.

The case study is based on analytics on historical operational data from the last 2½ years. The ferry is in an all-year operation. Data consist of 57 data points logged with 30 seconds resolution and is stored in a cloud solution. Each ferry approximately has 6.000 crossings per year giving a total of 15.000 crossing for this case study. Lately data logging has been established on both ferries doubling data sets and providing data for future studies comparing the two ferries.

Fig.6 depicts examples of ferry tracks. Data is from https://www.marinetraffic.com/. As seen, most crossings are direct between the two ports Spodsbjerg and Tårs. Longer routings are also used due to traffic or to improve passenger experience if the sea state is rough. The dashed lines indicate the outer boundary of the typically used area when crossing, so any data points outside of this area will be removed as outliers. The easterly part of the route is a dredged channel.

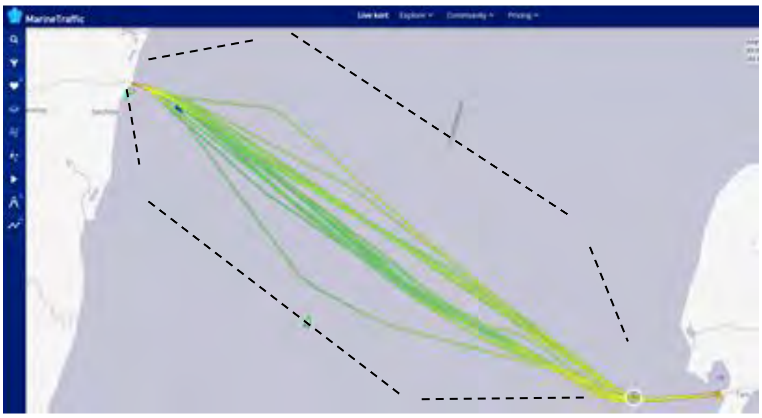

Fig.6: Tracks example from MarineTraffic

The operational datasets have been labelled according to the updated model shown in Fig.5 including the additional information with regards to wind, current, sea state [FCOO (2021)] and AIS traffic information.

Fig.7 shows an example of total power delivered to the four thrusters during 8 crossings marked 1-8. The higher power demand at crossing 1, 3, 5 and 7 is due to a strong headwind. As seen in the example the power demand is 80 % higher going upwind than downwind. The circles frame the time berthed i.e. in harbour mode (A-G), where it would be possible to charge batteries. As seen at “F” approximately 11 minutes are available, whereas the next port call “G” only gives a 5-minute window to charge. The consequence of the very short time for charging "G" could be the need to charge with more than triple power to transfer the same amount of energy, as opposed to if the time in harbour mode had been the optimal 15 minutes.

Fig.7: Total power

Fig.8 depicts how many minutes in percentages the ferry was in '*harbour mode'*. All 15000 trips are taken into account. The new optimal time in '*harbour mode'* ready to charge should be as close to 15 minutes as possible. The aim is to maximize time to charge, and it should be avoided to have port calls longer than 15 minutes, as this causes faster sailing to catch up and arrive according to schedule. The crew gave many valid reasons why only 50% of the port calls of today are in range of 12-15 minutes, but this needs to be addressed and improved if the ferries in the future are powered by batteries. This will be described in section 4.

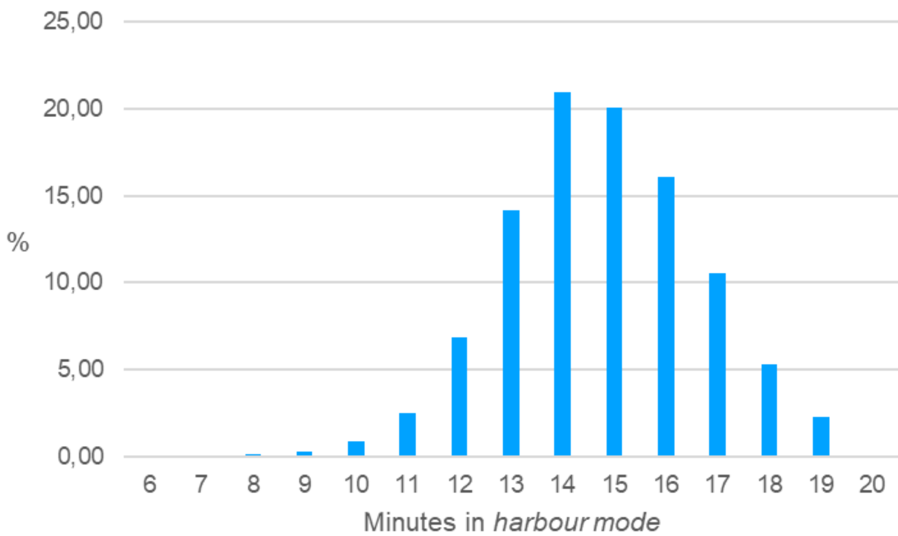

Fig.8: Minutes in 'harbour mode'

Another important operation issue when shifting to battery power is a transparent charging strategy to ensure robust, flexible operations and long battery lifetime. The lifetime can be prolonged by using partial-discharge cycles, avoid over charging or deep discharge, limit the battery temperature, avoid high charge and discharge currents.

The historical data can be used to explore and develop charging strategies e.g. the following issues could be taken into account:

- Needed reserve – summer/winter, last trip of the day
- Price - spot market, contract, own production
- Battery lifetime - slow charge and discharge

Fig.9 shows different examples of charging strategies in relation to the thrusters' power consumption. The power data is taken from Fig.7 trip 1 and 2.

- A = charge to maximal State of Charge (SoC) with different charge rate
- B = charge with same rate
- C = minimal charge e.g. due to currently high power cost

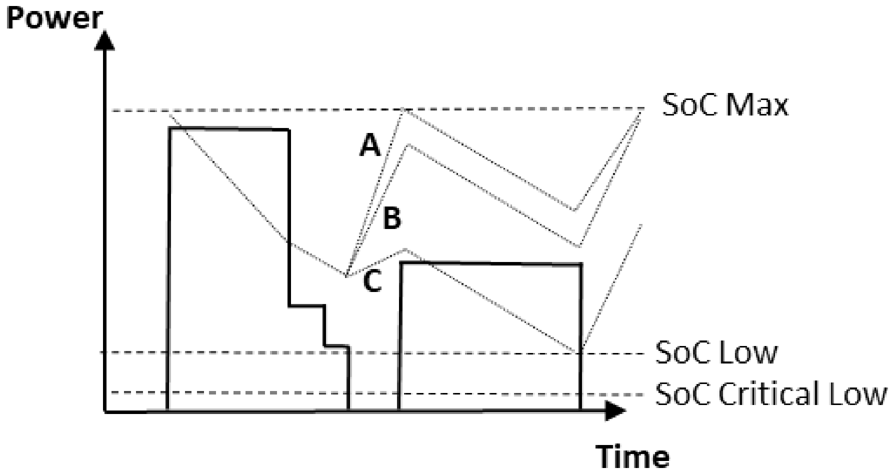

Fig.9: Power and SoC

The new framework described in section 4 can be used during the initial design process. Considerations regarding different power source configurations are briefly described. Fig.10 shows an overview of different energy scenarios when retrofitting the ferries. Scenarios 1 and 2 are related to grid connection, whereas scenarios 3-4 aim for zero emission using own premises. Scenarios 5 and 6 are relevant if there is a surplus of energy and customers requesting charging for their cars and trucks in harbour or during crossing. Some of the diesel generator sets already installed will be kept in place to provide a robust backup system. The onboard ESS can be configured in smaller redundant systems, to improve operational stability. It should also be noted that the grid connection fee in Denmark highly depends on power request, availability and how fast it is allowed to ramp up and down.

Scenario 1: Direct grid supply is a well-proven and used approach. The solution has a high peak power demand.

Scenario 2: Harbour ESS increases stability and reduces the peak power demand, thus potentially lowering cost.

A Harbour ESS is needed in the following scenarios.

Scenario 3: Installing wind turbines at the harbour area in Spodsbjerg and Tårs. Wind is also a well proven technology and can provide power all year even during the dark winter.

Scenario 4: Solar power, PV (Photovoltaics) could be installed the harbour area e.g. partly as carpark structure, but the production will be very low during winter and an alternative energy source is needed.

Scenario 5: Charging of cars and trucks in the harbour by surplus of energy from own production (scenario 3 + 4)

Scenario 6: Charging of cars and trucks onboard the ferries by surplus of energy from own production (scenario 3 + 4)

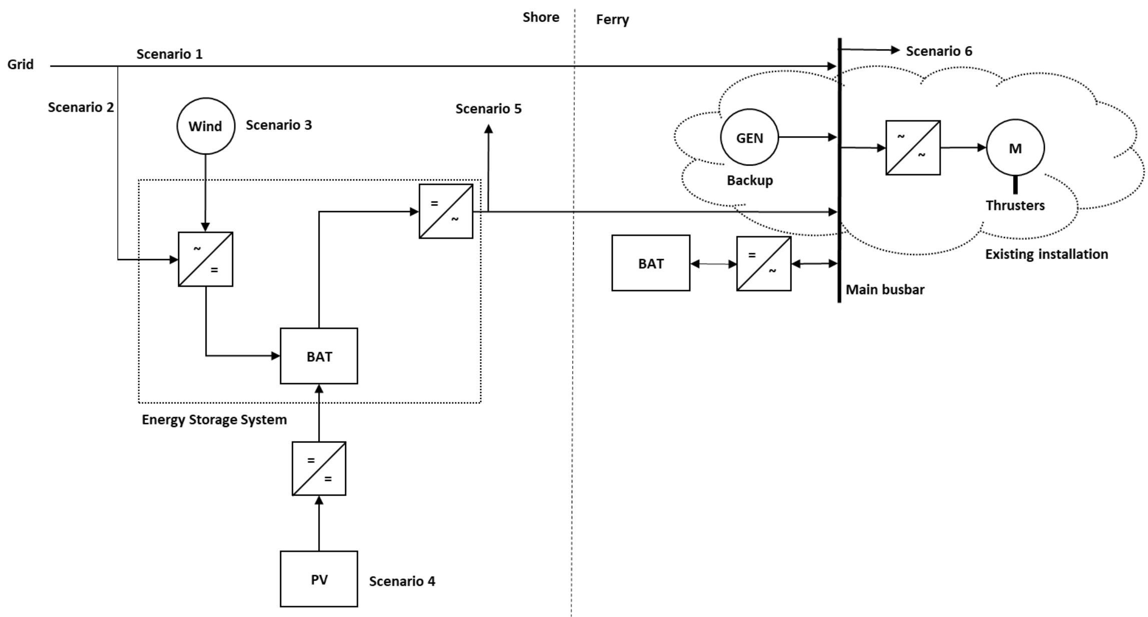

Fig.10: Overview

Finally, a number of unstructured interviews with the crew onboard the ferries showed great interest for a semi-automated berthing system to improve berthing operations and thereby increase time available to charge. The focus on a semi-automated berthing system will be part of future work.

The interviews also put focus on concerns with regards to stability and robustness of pure battery operations. The following main concerns were raised and should be addressed:

- charge connection out of service
- ESS land out of service
- ESS onboard failure
- No power from public grid is available
- time to charge
- backup options

Among others ABB [BONAVITA (2008)] uses the concept of "Comfort zone" in the context of oil and gas production. "Comfort zones" in the oil and gas production are the bands between production constraints and the actual production values. In Fig.11 a "Comfort zone" is shown as the area between SoC low and SoC Critical Low in Fig 9. The goal is to lower the "Comfort zone" the most to minimize battery size due to better battery utilization, and still achieve robust operation.

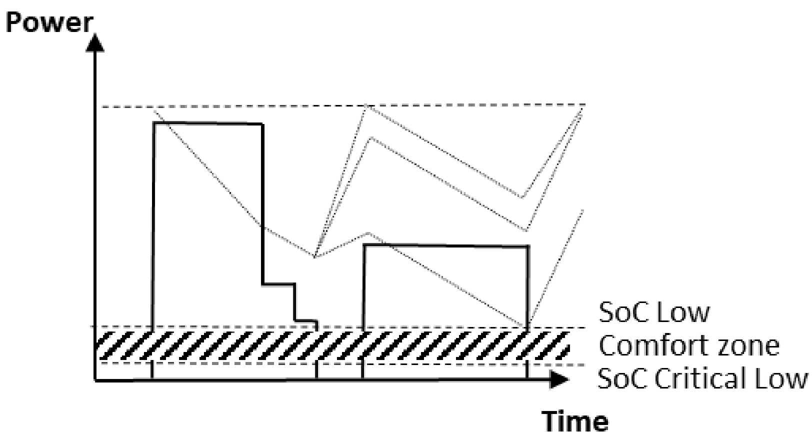

Fig.11: Comfort zone

4. Energy Decision Support System Framework

In this section a new Energy Decision Support System Framework is proposed. The operational goal is first and foremost, to generate energy- and cost-efficient charging plans.

The optimization problem is multi-objective and there are a number of approaches to solve it. To support a high degree of flexibility the new framework is proposed to consist of the following main components:

- a Multi-layered Energy Decision Making Support System [MIKKELSEN (2013)] based on genetic algorithms
- a labelling system based on the model in section 2
- a standard DAM (Digital Asset Management) system for storing and managing data
- a ML (Machine Learning) system constantly looking for improvement candidates
- an improvement candidates list system

Fig.12 depicts a data flow overview. Data to the DAM system comes from multiple sources like wind, sea state, energy production etc. Data is time synchronized and consolidated in the system. The operational data is labelled with mode/state information prior to being stored in the DAM system. The multi-objective optimization marked "Task 1" is a continuous process and shall provide updated charging plans, whereas "Task 2" is a background process searching for improvement candidates.

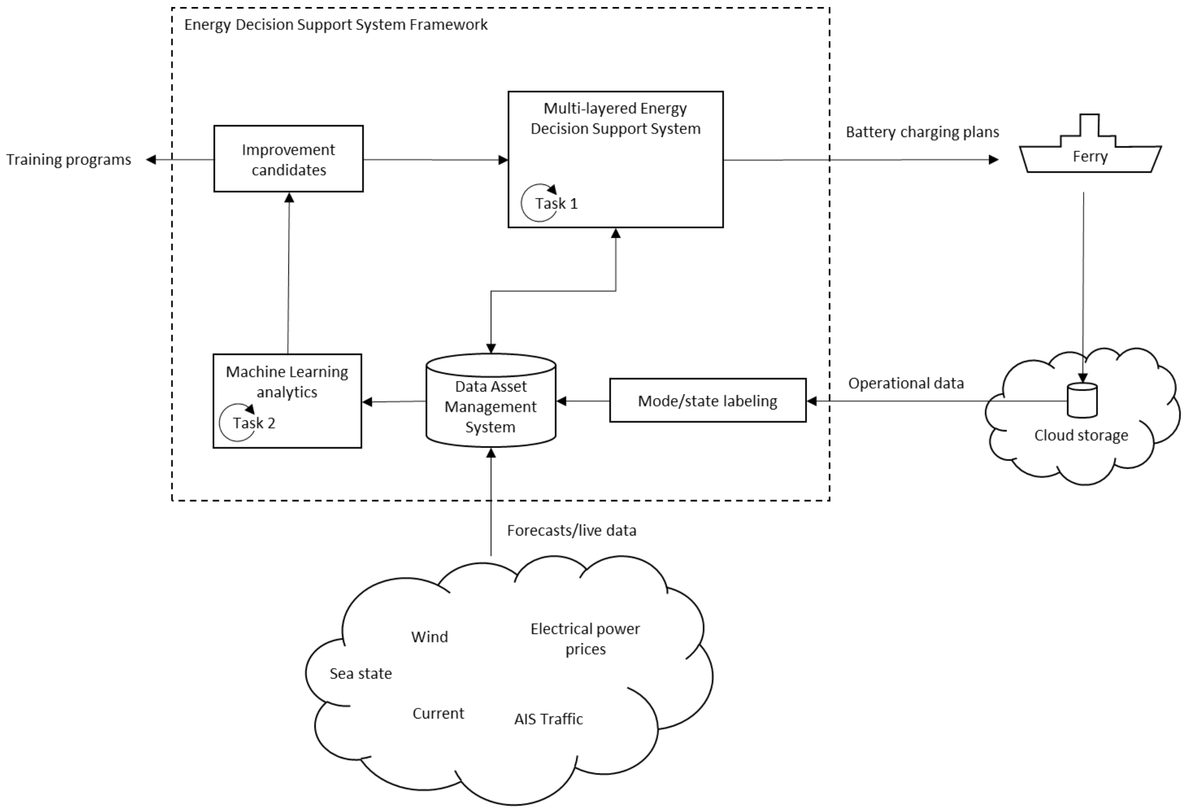

Fig.12: Conceptual data flow

Regarding task 1:
To decouple the problems the multi-layered decision is used, and problems are split into smaller concerns. The concerns can be divided in two groups: hard and soft. The hard concerns are restricting the solution's space and need to be fulfilled at all times, whereas the soft concerns are flexible to utilize the solution elasticity.

Examples of hard concerns where the solution space is confining could be:

- SoC critical low
- Maximum charge current
- Maximum battery temperature

The soft concerns utilizing the elasticity in the solution space could be:

- Prolong charging
- Minimize charging
- Maximize energy profit

In this first system test, the problem solving is only executed by genetic algorithms, but it will be possible to use different problem solvers in each solution context. As there is no complete mathematical model in place, the approach by *Simon (1956)* currently finds the best solution. Whether it is the optimal one cannot be checked.

The soft concerns need to be labelled with importance (weight) and priority (ranking) to avoid the solution's space being biased by less important concerns. Before new concerns are set into operation they need to be validated and thoroughly tested in a test system. When tested and approved a new concern can be loaded into the running system by being introduced with low weight and priority. These can then eventually and slowly be increased to the correct values.

Regarding task 2:
Preliminary results using Wards' Linkage unsupervised machine learning are promising and will be presented in a future study.

5. Conclusion

The mode/state model is updated to reflect battery operation of ferries and the new model was used to label historical data used in the case study.

The Energy Decision Support System framework is also updated and extended to fully support battery operation of inland ferries both as new builds and retrofit. The framework can now be used to qualify design, create charging plans, and identify improvement candidates during operation.

The case study shows it can be very challenging to find an energy balance that is both robust and cost efficient if own energy production in the form of wind and PV is taken into account. The study also showed that only 50% of the port calls today are in range of 12-15 minutes, so this needs to be addressed and the development of dedicated training programs is proposed. By optimizing the time available for charging the battery size can be reduced significantly and thereby reduce overall installation cost. This can further be improved by increasing operational energy efficiency and by generating efficient battery charging plans.

The main focus for the future work is to create an open-source system which can be used in the design process and afterwards in daily operations. This is to support the transition from fossil fuel to sustainable energy sources.

Acknowledgements

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A Method for Evaluating Ship Concepts in Realistic Operational Scenarios using Agent-based Discrete-Event Simulation

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Abstract

Meeting IMO's greenhouse gas ambitions generates need for designing low- and zero-emission ships within the maritime industry. Evaluating proposed conceptual ship systems in terms of energy efficiency, exhaust emissions and operability is a task of great complexity, even more under realistic operational profiles and weather conditions. This paper presents a simulation method developed for evaluating a ship concept across several years of realistic operation. The method allows for a user-defined operational scenario and simulates numeric hull, propulsor and machinery models based on agent-based discrete-event simulation in historic oceanographic data. A use case for a tanker is presented, demonstrating how the method, implemented through a simulation software, helps the naval architect in navigating among the various technologies available, being able to assess an early system design in a scenario spanning several years.

1. Introduction

A ship can be identified as a complex system made up from numerous sub-systems, such as main and auxiliary engines, crew and passenger cabins, cargo spaces, cranes, and other handling equipment, as well as the hull itself and the propulsors. Finding the right design and combination of sub-systems for the ship to perform optimally throughout its life time and considering the unknown future, is a difficult multi-objective optimization problem to solve, if not an impossible task, *Bertram and Thiart (2005)*. Notwithstanding, given the urgent need to maintain and improve the cost and carbon competitiveness of waterborne transport, this task is worth trying.

The ship design process has been evolving for several decades since the traditional design spiral was introduced, *Evans (1959)*. Despite the increased availability of computer-aided tools in the 1980s and introduction of system based design method in the 1990s, *Erikstad and Levander (2021)*, which is meant to be an iterative method, ship designers tend to lock the main dimensions of the ship concept early in the design phase, based on experience or tender requirements. Investigations of various energy-saving devices such as wind-assisted, *Lu and Ringsberg (2020), Tillig and Ringsberg (2020),* and wave-assisted propulsion, *Stensvold (2020),* are expected to change how a vessel is designed and operated, *Tillig et al. (2020)*. The current lack of operational experience means risking that the initial ships using such devices may not live up to the expectations compared to the increased investment costs, and such devices may be dismissed on faulty basis. This underlines the importance to uncover the true requirements of the vessel early in the design phase to come up with designs that performs well throughout its lifetime.

Holistic ship design focuses on finding the true functional requirements of the vessel by looking beyond the ship itself and into what the ship is intended to, and maybe just as important, will do throughout the future. Logistics Based Design considers the ship as part of a logistic system with the goal of doing transportation work between two ports, *Brett et al. (2006)*, and extending it into a life cycle approach considering the performance of a design from the keel is laid and eventually including being scrapped, *Papanikolaou (2010)*. Further, moving the scope of the design task to consider all vessels serving as part of a transportation system also including other forms of transportation, such as land-based (multi-modal transport), can help the designer to come even closer to an optimal global solution, *Hagen (2020).*

Gaspar et al. (2012) identified five aspects of complexity in ship design, namely:

- Structural: How sub-systems of the vessel interacts.
- Behavioural: Analyse how each sub-system performs individually.
- Contextual: The external context the ship is subject to, such as different operational profiles.
- Temporal: The change of all aspects of over time, that is for instance changing operational requirements.
- Perceptual: How advantageous different designs are for various stakeholders, such as owner, operator, and client during different epochs.

A simulation-based evaluation method that can integrate several sub-systems and assess the performance of the ship concept both in an environmental and economic manner seems advantageous for covering several aspects of complexity: the system interactions (behavioural complexity), the effect of operational profiles (contextual complexity), the change of static contexts over time (temporal complexity) as well as to allow the other stakeholders than the designer to do independent evaluations from their point of view in the perceptual aspect. Coupled to a generic ship synthesis model, *Lagemann and Erikstad (2020)* the combination of methods would allow for quick and intuitive way of assembling, analyzing and evaluating a ship designs at a conceptual level.

With increased availability of computational power, simulation of a ship's sub-systems is now a common discipline, and a lot of effort has been put into integrating several sub-systems into a grander ship system model. By defining standard interfaces, dynamic simulation models of various sub-systems developed by their respective vendors can be integrated, *Hassani et al. (2016), Sadjina et al. (2019), Skjong et al. (2018).* The coupled simulation model essentially becoming a large set of differential equations can be accurate, but tends to be computationally demanding to solve, and applying longer simulation horizons than a few days in not practical.

Using simulations to benchmark a a whole ship system in realistic operational conditions over a lifetime period requires a method that allows for simulation horizons on the scale of years. By simplifying the ship model to a quasi-static representation, the number of sampling points can be greatly reduced, still revealing significant performance differences between ship designs, *Fathi et al. (2013)*. The validity of such a method was confirmed by *Sandvik et al. (2018)* through a case study using full-scale measurements from a deep-sea vessel, and also extended to a more complex ship model including a machinery model, *Nielsen et al. (2019)*. The same approach has also been implemented in a software suite and tested by the industry, *Erikstad et al. (2015)*, and applied to use-cases for a RORO-Ferry, passenger ferry and Offshore Supply Vessel to prove its ability to produce operational profiles, *Yrjänäinen et al. (2019)*. The route of a vessel between two harbours are by no means static between voyages due to weather routing and the captains choices, and the effect of such variations were found significant, underlining the importance of modelling realistic scenarios in the simulations, *Sandvik et al. (2020)*.

Based on this work, this study presents a simulation method for early-phase concept evaluation that applies agent-based discrete-event simulation to quasi-static ship models (known as the "Gymir" simulator in the funding project) and demonstrates how it may be used to compare design variations in the design process.

2. Simulation method

Fig. 1 illustrates a high-level sketch of the goal of the simulation method. Inputs to a simulation are:

- A scenario, consisting of waypoints defining a route, speed-policies and timestamps for simulation start and end defines how, where and when the ship will sail.
- Historic oceanographic data, typically from a hindcast/re-analysis model that covers the geographic and time domain of the scenario.

- A numerical ship model that given a sea, -and weather state, calculates the necessary power to maintain a desired speed (i.e., quasi-static)

For an efficient evaluation of these models, the simulation method should only re-evaluate (sample) them when there is a significant change in any of them. Typically, such changes are:

- Reaching a waypoint, triggering a course change for the ship, which consequently changes the encountered wind-, and wave direction.
- There is a significant change in the weather, e.g., the simulation a new cell in the discrete grid of the weather data.
- The speed or power plant setting of the ship is altered.

During the simulation, all the evaluations are logged into a time series, and the performance of the ship model is analysed.

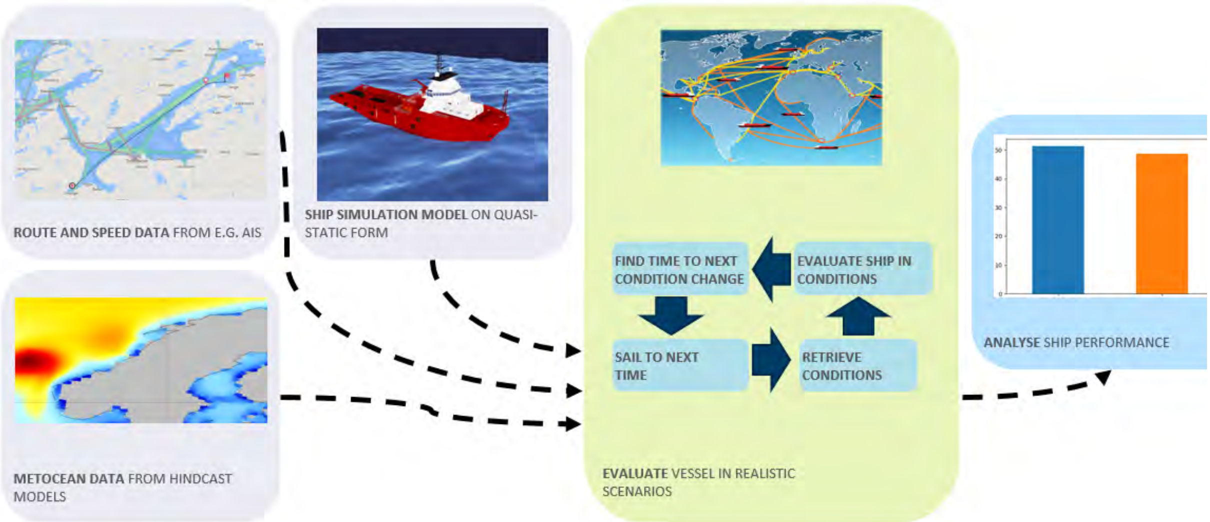

Fig.1: High-level concept sketch of the simulation method

The Agent-based Discrete-Event simulation approach defines parts of the simulation an agent, which at each time step reports back to a central scheduler what should be an appropriate time step to the next sample. The scheduler evaluates the reported time step from all agents, selecting the shortest one. All agents are then evaluated at this time, resulting new time steps are reported to the scheduler.

In this paper, one such agent is the ship, which reports to the scheduler the time required to reach the next waypoint given the current sailing speed, while the weather data is another agent, reporting the next time new data is available. Thus, the relevant changes along the timeline in a simulation scenario are dynamically steering the simulation time step, rather than having to force a significant number of costly samples to ensure that changes in the weather data is covered. Fig.2 illustrates how the simulation method will choose timestamps for sampling.

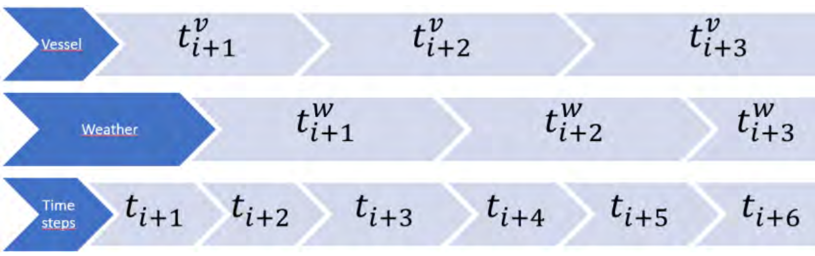

Fig.2: Illustration of the Agent-based Discrete Event Simulation approach used in the ship performance evaluation, *Yrjänäinen et al. (2019)*

3. Ship models

To demonstrate the evaluation method, a case study is constructed by modelling two fictional ships. The first has a typical shape for a Medium-Range tanker of 174 m length (Benchmark), the second is prolonged though slightly slenderer (Slender). Both ships have approximately the same cargo capacity and fit within the old Panamax canal. A ship designer may have a hypothesis that the slender design will outperform the benchmark due to lower wave resistance. This hypothesis can be tested using the simulation method described in Section 2.

Both ships are modelled using the ShipX numerical software package, *Fathi (2018), Fathi and hoff (2017)*, which is based on a 3D-model of the hull and uses potential flow strip theory to compute the residual resistance. Combined with an open water curve for a propulsor, the required power and RPM to attain a speed through water are estimated for any significant height, peak period and mean direction of the waves and average wind speed and direction. Fig.3 shows the hull of the benchmark ship; Table I lists some main particulars for each design.

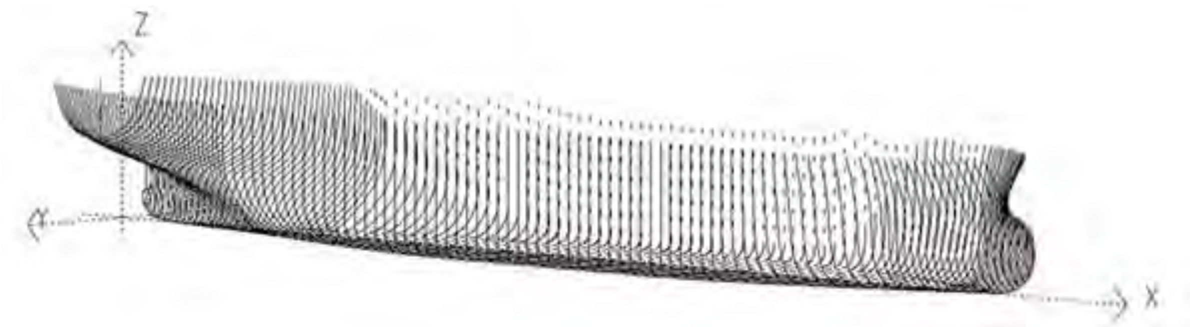

Fig.3: 3D-representation of the hull for the benchmark ship

Table I: Ship model particulars

	Length	Breadth	Draught	Block
Benchmark	174.0 m	32.2 m	11.0 m	0.782
Slender	190.0 m	32.2 m	11.0 m	0.728

The required power to keep a desired speed will vary with the sea- and wind state. As the power plant models in this paper are simplified to deliver a desired power to the propeller shaft, a power control policy more advanced than keeping a constant power is needed to achieve a realistic simulation. Two power policies can be set for the simulation, namely:

- Keep constant speed by varying the power, though if above a limit (e.g., maximum available power), reduce the speed so that power is equal to the limit. This policy may be applicable to ferries, which are required to keep a strict time schedule.
- Vary power (and speed) to keep a constant propeller RPM. This policy is commonly used on deep-sea vessels.

Note that only the power applied to the propeller shaft is considered in this paper. Other consumers such as hotel loads are neglected as they are considered independent of the ship hydrodynamic shape.

4. Scenario

A common transport assignment for a MR Tanker is carrying oil from the east coast of North America to Western Europe. A representative route is constructed from the Gulf of Mexico to the English Channel, and typical waypoints for such a route are visualized in Fig.4, *Admiralty (2018)*. Yellow markers indicating the end points of the route, while the orange markers represent waypoints inserted for navigation.

Fig.4: Visualization of the route used for the simulation

To demonstrate the simulation method, the ships are set up to shuttle this route back and forth, excluding the port entrance and loading / unloading time from the simulation. This pattern is repeated throughout one year from January 1st 2018, until December 31th 2018. The speed policy is set to keep a constant speed of 13 knots and simulate a powerplant by limiting the propulsion power to 8000 kW. Historic weather data from the European Centre for Medium-Range Weather Forecast's ERA5 re-analysis dataset is used, *Hersbach et al. (2018),* p.5.

5. Experimental simulations

Simulating each ship requires approximately 4 minutes running on a relatively standard laptop (Intel i7 8650, 16GB RAM), resulting in 3039 and 3041 sampling points for the benchmark and slender ship simulation, respectively.

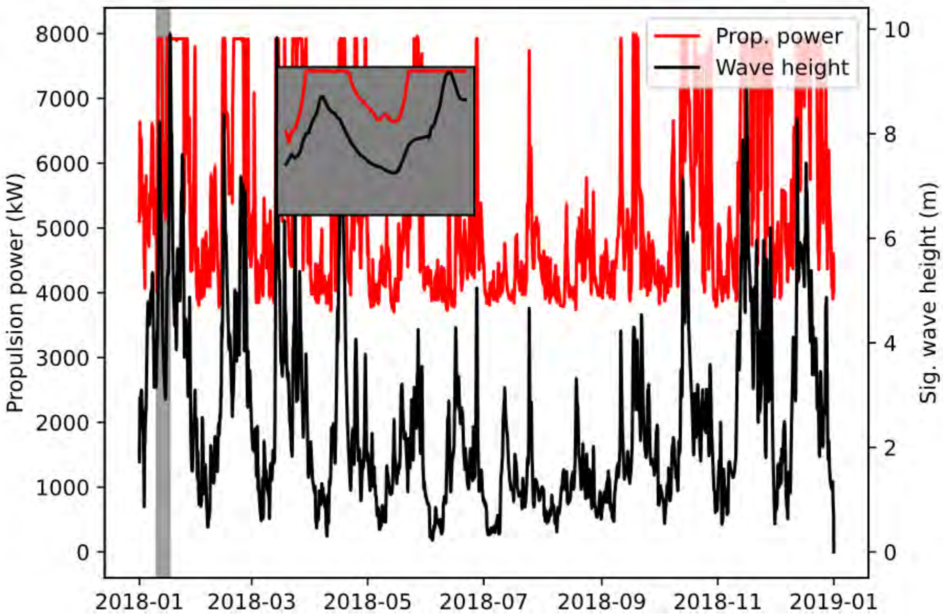

Fig.5: Time series of encountered wave heights and propulsion power for the benchmark ship

Fig.5 shows the encountered significant wave height and resulting power consumption for the benchmark ship during the simulation. It can be noted that on several occasions, when relatively heavy weather is encountered, the power consumption reaches its maximum limit, and the sailing speed is reduced to attain the power limit.

A selection of one week, starting at January 10th, marked in grey on the time-axis, is shown in the grey detail plot to illustrate the level of detail in the simulation.

The effect of the two ships having different added wave resistances is illustrated in Fig.6. Each ship's accumulated sailed distance is subtracted from an "ideal" case sailing at 13 kn for the whole year, regardless of wind and waves. The figure shows that the slender ship is less prone to reaching its power limit due to less added resistance. This in turn results in the slender ship keeping a higher average speed than the benchmark, accumulating a lead as the simulation progresses.

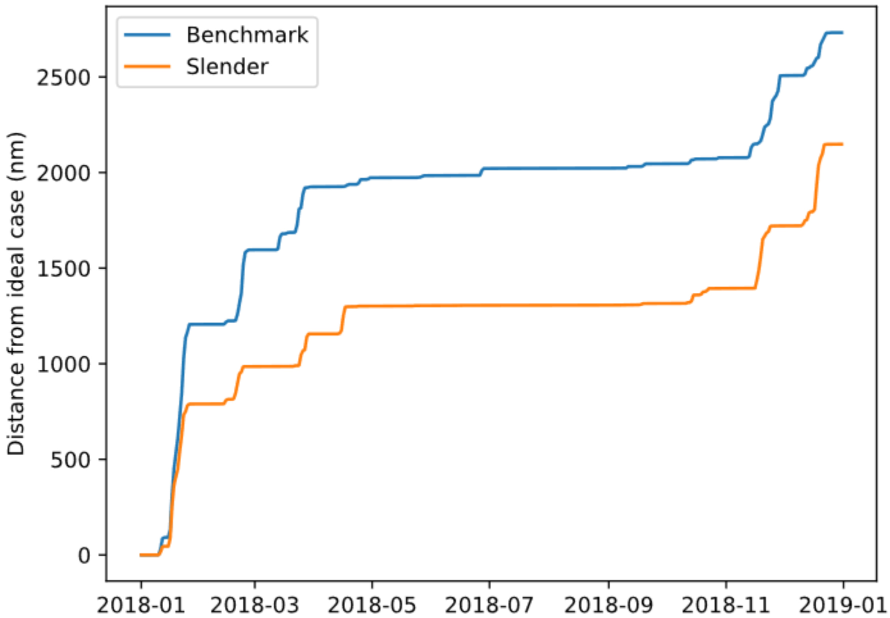

Fig.6: Simulated distance of the two vessels from an "ideal" vessel not exposed to (involuntary) speed loss due to weather

The varying geographical progress of the two simulations inevitably leads to the ships encountering different weather, Fig.7 shows a histogram representation of the waves encountered by the two ships during simulation. The difference may increase due to the lack of active weather routing in the simulation, as the ships will encounter rough weather that the captain in cooperation with weather routing would have avoided by alternate routes and speeds. The highest wave height encountered in this simulation is 10 m significant, which is a rare and undesirable event for a merchant ship, and thus should not have any weight in the design optimization process as it gives the slender vessel an irrelevant advantage. This may be solved by implementing a logic that adapts the speed and route to avoid heavy weather, or simply remove the simulation samples where it occurs. The former method will typically complicate the interpretation of the simulation results, as the two ships may end up sailing very different routes, while great care must be taken using the latter method to avoid removing sample points that have a significance to the design process. As of this, the results are left as-is for the purpose of this study.

The average significant wave height of the encountered sea states is very similar for both vessels. The distribution differs though, highlighting the importance of considering actual sea states rather than averages.

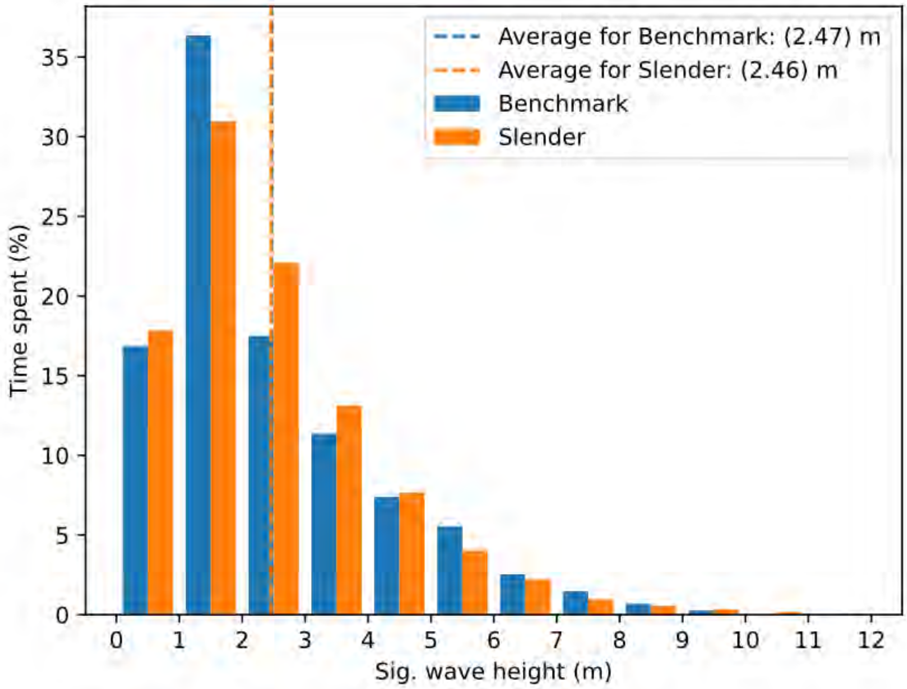

Fig.7: Resulting histogram of encountered significant wave heights

Fig.8 shows a histogram representation of the power consumption for both ships for the whole year. As expected from the lower added resistance, the slender vessel has a reduced accumulated energy consumption, and generally outperforms the benchmark in significant sea states. Such an analysis may form a basis when dimensioning and optimizing the power plant, giving insight into how often a smaller, more efficient power plant will be insufficient to keep the design speed. What load point the power plant should be optimized for, as well the expected variation can be extracted from the data, both factors being desirable to minimize.

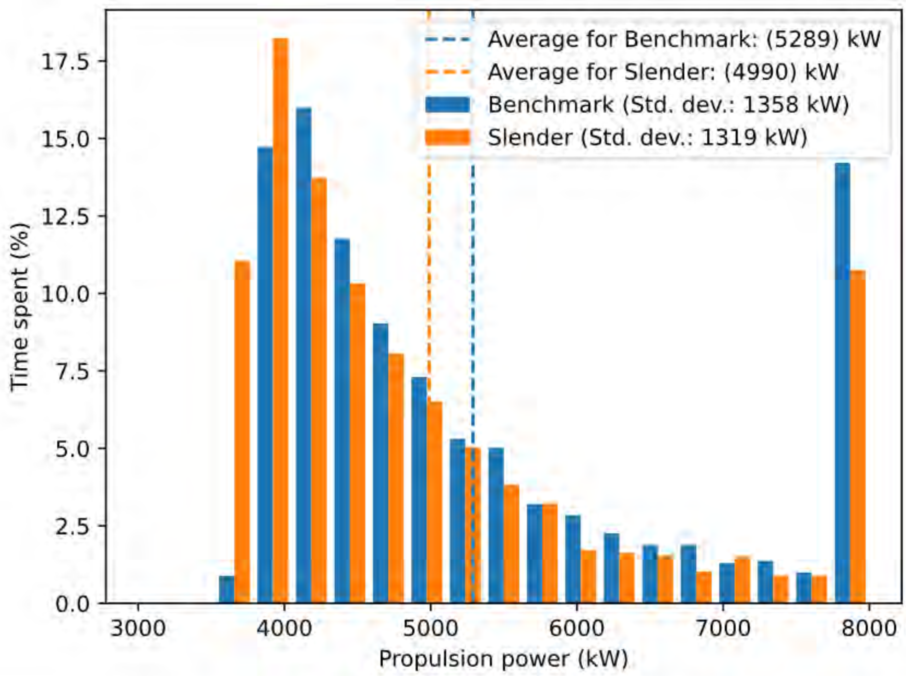

Fig.8: Histogram of propulsion power consumption during simulation

As a last example for what insight a simulation across a long-term horizon can give, Fig.9 shows the wind directions encountered relative to the vessel. This may be used as a basis for optimizing the superstructure with respect to air resistance or, more importantly, to consider the effects of wind-assisted propulsion, and what type of sail that may be the most promising for the scenario that the ship is intended.

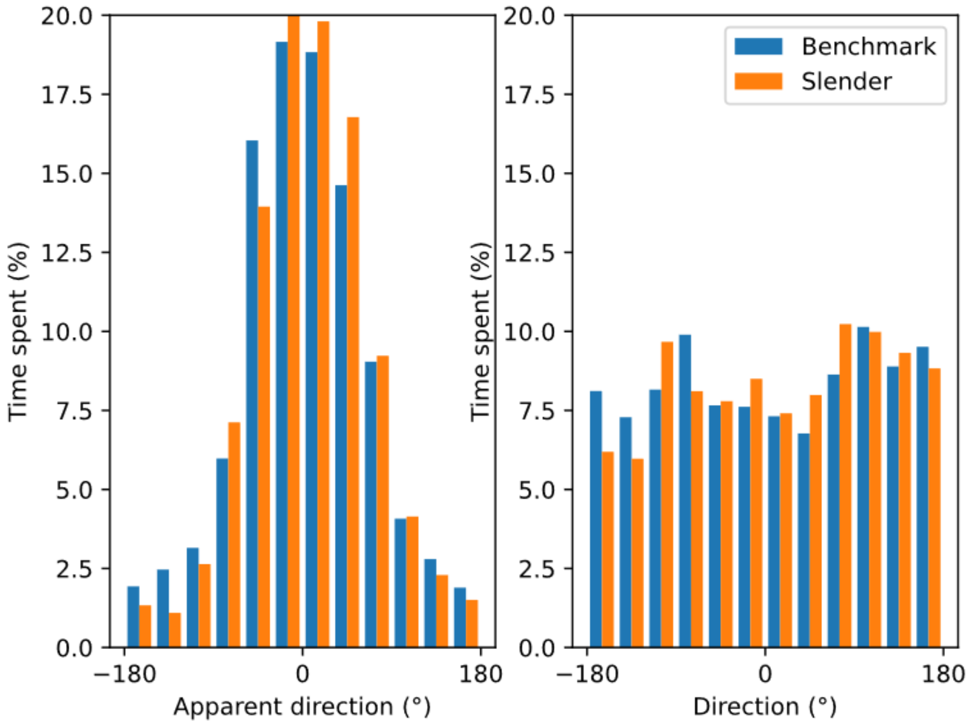

Fig.9: Wind direction relative to the ship. Left plot shows wind direction as apparent to the ship while sailing (left) and wind as apparent to the vessel if standing still (right).

6. Conclusion and further work

A simulation approach for efficient evaluation and benchmarking of a ship concept in a realistic scenario and weather conditions across long-term horizons were presented. Two alternative numerical ship models were introduced, along with a scenario comprising a representative route for the ship class, power plant policies and sailing speeds.

Thanks to the dynamic agent-based discrete-event simulation technique, the long-term simulations (one year) could be carried out efficiently in a matter of minutes. With the speed-up in computational time, our method allows for simulating and exploring further alternatives, whether iteratively or simultaneously.

In general, our method enables moving from calm water evaluations towards real sea states early in the design process. However, it does not come without difficulties: With the ships having different behaviour in similar environmental conditions results in a deviating operational profile as the simulation progresses, complicating the comparison of the results from the ships. Also, the lack of any active weather routing occasionally leads to irrelevant conditions, underlining the need for further work on how the scenario is modelled and simulated.

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KBE/AI for Ships Construction - A Feasibility Study

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Abstract

After about 60 years of CAD in shipbuilding, we are currently entering the 3rd generation of CAD software: The generation that leverages the power of Artificial Intelligence (AI). These topics will strongly increase the future development and the maturity of CAD/CAM. The KBE (Knowledge Based Engineering)/AI (Artificial Intelligence) for Ships project is the development of an intelligent software system which contains a great number of special knowledge and expertise on shipbuilding constructions and assembling. Based on this knowledge and expertise stored in the system, the expert system must apply artificial intelligence and computer technology to simulate the decision-making process of human experts to reason about, judge, and finally solve, complex issues. In the recent times, influence of AI, Cloud Collaboration and VR, has expanded rapidly, where MasterShip's position in Maritime industry can play an important role for these developments. This paper also briefly explains the results of the Innovative approach and detailed technical feasibility performed by MasterShip on different cases.

1. Introduction

Nowadays it is a common problem that the detailed engineering and work preparation for ships is done by inexperienced young engineers in the drawing room where this was done by experienced workers at the shop floor before. At this point, Mastership is ambitious to introduce a virtual system called "Knowledge Based Engineering" for ships (KBE for ships) especially at this stage of the shipbuilding process. This means we want to make virtual use of the practical knowledge of experienced workman and technical constraints during the detailed engineering and the work preparation. Therefore the KBE for Ships system will be a software system that makes decisions by simulating the problem-solving process of human beings. Based on this knowledge, expertise and constraints that will be stored in the system, the expert system must apply artificial intelligence to simulate the decision-making process of human experts to perform reasoning and make judgments, and finally solves complex issues. Design and engineering has always been the interesting and most complex phase for ship construction where to keep the information in order has never be easy. A conventional approach for such phase is presented in Fig.1.

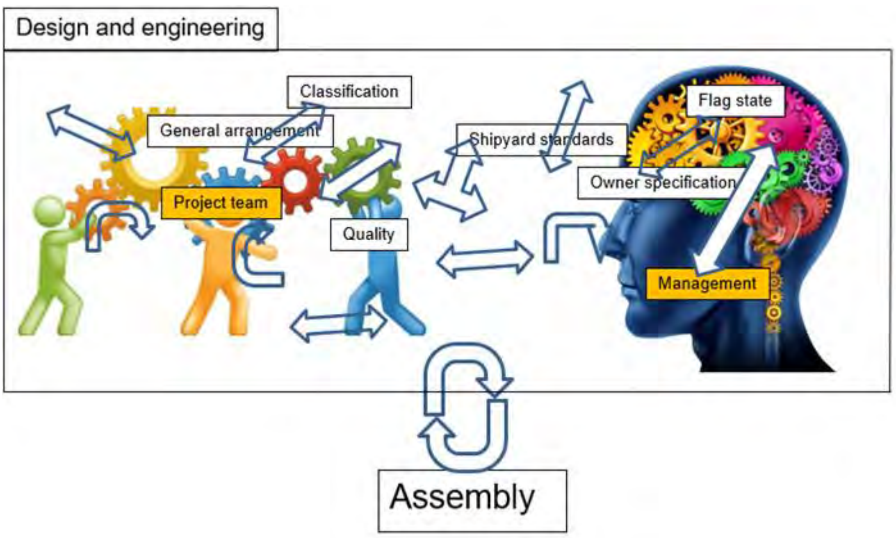

Fig.1: Conventional approach

We, at MasterShip, believe that most of the things done in the design office can be replaced or better managed with a help of knowledge based systems, i.e. expert systems, Fig.2.

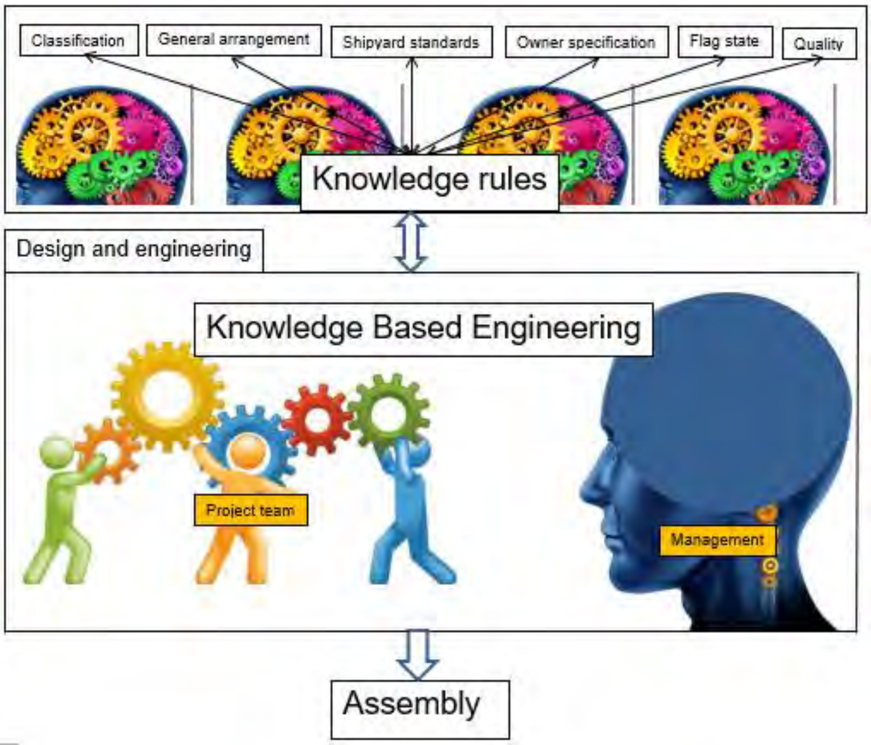

Fig.2: Basic concept of expert system

2. Literature review

Automation in ship design and engineering is introduced since mid-sixties of the 20th century. About 10 years after the first experiments on CAD/CAM in general in the fifties of the 20th century, *Dokken (2012)*. Since this introduction of CAD/CAM there were many developments as well as in software as hardware that had great influence on the design and production process of ships. CAD/CAM Was a new industry and today we can conclude that there are still some immature effects. A few remarkable points are:

- Isle of automation: All kind of specific process steps where automated. As well over different involved disciplines as hull, HVAC, electrical, interior and mechanical as over the same discipline but divided over the sequential process steps like concept, basic, detailed and production design.
- Lack of digital communication: Even lack of conventional communication! It appeared to be hard to pass on data to other design and engineering stages.
- Changing processes: The design and building process changed as a consequence on the CAD/CAM development. For instance:
  - 50 years ago, parts of the detailed design and the full production process was done entirely non-digital on the shop floor and lofting floor of the shipyard and is done now fully digital during the last stages of the design and engineering process.
  - Another example is that the design and engineering process stages are growing into each other. The boundaries between the stages concept, basic, detailed and production design the stages are grey and the tasks over these stages are more and more integrated.
  - Simultaneous engineering: work on more disciplines can be performed at the same time and earlier in time than before.
- Earlier need of information and decisions: Because many process stages can be performed earlier and in more detail the information on equipment and details is needed earlier in the

process. Anno 2015 the still appears to be a challenge. It is also noticed that an old rule that was also valid in non-digital design and engineering is still valid: the earlier a mistake is found the cheaper to solve it. Or the other way around: the later a mistake is found the more expensive to solve it. In CAD/CAM it seems obvious that a mistake in the digital phases (concept, basic, detailed and production design) will almost always be cheaper to solve than a mistake at the shop floor.

Above mentioned dots lead to several "Gaps and Overlaps" in the design, engineering and assembly of ships. The costs involved in these Gaps and Overlaps are estimated at 20 % of the total project costs, *Moyst and Das (2005)*.

3. Requirements

Knowledge Based Systems are mostly based on so-called rule-based systems in which heuristic rules are used to encapsulate knowledge from human experts. A knowledge engineer captures these rules during sessions with a human expert, in which think-aloud protocols are used to extract the used knowledge. Subsequently this knowledge is encoded in the form of IF-THEN rules and used by an inference engine, which applies the knowledge to projects in which this knowledge is required.

In some cases, the expert who makes comments while using a CAD system may also propose new rules during the design process and later extend these notes into full rules. Also some systems use machine learning to automatically acquire such knowledge. Because the existing software of MasterShip is based on AutoCAD, this should be target of any possible solution.

So in general, the following functions should be made available to be included in the proposed software:

1. A facility to note and register required KBE facilities, preferably during the design process. This may help in identifying missing functionality. It is mostly used to register where a need exist for expert advice. A first list of known requirements would be a good start.
2. A facility or method to acquire the identified knowledge. This will mostly be based on Knowledge Engineering principles.
3. An open-source inference engine that can be embedded in the AutoCAD environment. We will investigate what libraries are available and how well they fit into the requirements.
4. A facility to encode and test the rules with the proposed system. Because maintenance of a knowledge base can be a daunting task, good verification and testing facilities are a very important requirement. There should be a number of test projects in which all designed rules are tested. There should be a complete regression test environment that allows testing of the entire system and its facilities after every modification.
5. A system to automatically document the acquired rules so the users may get a good idea of what kinds of checks and advice can be expected while using the system.

If possible, the inclusion of an explanation facility should be included to explain to the users why a certain rule is being applied.

4. Scope

MasterShip encountered four main reasons to implement this research in the shipbuilding industry as knowledge based engineering:

1. Integrating general arrangement specification and classification - As well as for the primary as secondary scantling and their belonging details it costs a lot of time to design and engineer according to the applicable classification and/or flag rules. Classification Societies released software these days to find the right dimensions. Integration of the classification/flag rules into a knowledge based database for the CAD/CAM software will be a great step forward.

2. Using practical workshop experience at the drawing office - During the non-digital period when the production design of the ship was done at the shop floor the knowledge of how to build the ship was added by the workers at the shop floor. This added knowledge existed out of general shipbuilding knowledge and specific yard-oriented knowledge. The yard-oriented knowledge was based on the available stock, machinery, working space, cranes, storage space and employees' capabilities at the shipyard. Because this work was done in the real physical stage it was visible for everyone who was around. In the modern design and engineering process the work preparation is done in the virtual stage. Sometimes at the drawing room at the shipyard, sometimes at a design or engineering company elsewhere. Because the last decades CAD/CAM was a way of working that was more popular and only educated to younger people the people who did this modern digital and virtual engineering work did not have a lot of experience yet in general shipbuilding and also not in the yard specific shipbuilding. It was and still is a challenge to bring the shop floor knowledge to the drawing room. A knowledge base database can be of great help here.

3. Becoming a learning organization - Shipyard has to take care for their company knowledge. Many times, the so-called company knowledge is only stored in individual knowledge storage systems of employees. Sometimes it is stored in personal digital files or even in small personal non-digital notebooks. When people leave the company, the knowledge is lost. Companies can grow into learning organizations when they use a system that this knowledge is stored in as well as for storage low accessible as well as for retrievable low accessible knowledge database.

4. Automation of quality control - Quality control takes a large amount of time during the design and engineering process. It is evident that this time must be spent because finding mistakes as early as possible is much cheaper than finding mistakes in a later stage as for example in the worst case at the assembly stage of the ship. It is a challenge to automate a part of the quality control via the use of knowledge base engineering. It will enable to do things right at once instead of repairing afterwards which will definitely be will be a great step in the field of shipbuilding and maritime industry.

5. Feasibility study

In order to validate the concept and innovation proposal by MasterShip, a detail technical feasibility study was performed during the year of 2015-16. This technical report gives an introduction to the concept of Knowledge Based Engineer in product development. It discusses applications of KBE/AI and also describe the process of developing KBE-systems. A brief view of commercial KBE/AI software is given and then benefits and drawbacks with KBE is discussed as well. The report is finished off with some statements about the current research topics of KBE.

Some concrete findings of that report are being mentioned below for a better understanding of the previous research on this regard:

1. As described in the conclusions of the preceding sections, we recommend to first design a number of template interfaces between AutoCAD and a RuleBase system, using a simple sequential Rule Execution mechanism. This system can be built around the ShipHull example and form a Proof-Of-Concept application. It can be used directly for demonstrations or even be used as a small implementation of the KBE.
2. At a later stage, this system can be expanded with more knowledge and AutoCAD features and will then also require more facilities from the Inference Engine. This will form an integrated system, wholly proprietary, eliminating the need for a complicated language interface.
3. During the feasibility research, after completion of multiple test using inhouse inference engine, it is concluded that such system will be able to perform the neural network

characteristic which will lead us to machine learning of such data that is self-generated rules based on the decisions throughout the process.

4. We propose a two-phase approach, where in:
   a. first phase the code that is already available will be expanded to make a working prototype, with a mock-up Inference Engine.
   b. The second phase will expand upon this program and based on several tests with users be developed into a functional Proof-Of-Concept.

This will then form the basis for a later actual implementation, in which the other features will gradually be implemented. This system can grow by adding more problem areas and its associated knowledge. There will be many more AutoCAD interfaces and additional facilities in the Knowledge Base and Inference Engine.

5.1. Direction

There are at least two major parts for the a KEB system, Ship Design Data and a Decision Making algorithm, which may include optimization and machine learning algorithms. Now there are some open sourced tools or algorithms used for machine learning, which may be used in the Expert Systems. The Ship Design Data must be parameterized so that the algorithm can build the connections or rules between those parameters. I think how to parameterize the design data will need a lot of research, for the key parameters must be chosen and feed to the algorithm of machine learning. And it may need tons of data for the machine learning. For the algorithms, we also need to find the best one fit our area:

- Intelligent construction design - This is mainly for stage of ship construction detail design, to combine class-society rules and customized templates in the process of making construction design, with an interactive way. In industry of aviation and automobile, this technology has been widely used for many years.
- Ship hull surface division - That means to combine expert knowledge for the work of making seams/butts in an interactive way. Influence factors of hull thickness, curvature, construction lines arrangement, shipyard-workshop capability, etc. shall be included.
- Welding information add-on In the stage of work preparation, clients will ask for adding welding information in the building kit, such as welding length, material, method and green margin, etc., this kind of information is related to class rules and shipyard-workshop capability.
- Assembly plan - Every shipyard has it unique capability of manufactory and assembly, the best Assembly Plan shall match the feature of the shipyards and optimize the process of cutting, welding, coating, assembly, etc.

5.2. Long-term goal

The long-term goal of AI SH is that companies can become self-learning organizations. Learning by automatically adding new rules to the system. Self-learning by allowing the program to suggest the adaption of new rules. Finally, the goal must be that the AI SH program will not just check on rules but will implement the rules automatically as well. Also, the set-up of a consultancy company for advice on AI in the same domain is a long-term goal.

5.3. Machine Learning in the shipbuilding domain

Almost all rules and interfaces that have been identified so far are logical constructions that do not lend themselves for a machine learning approach. Learning the Rules of a RuleBase would require a large number of examples and associated solutions to allow automatic learning. Such situations may apply to certain other tasks in shipbuilding that were not present in the three examples that we investigated.

6. The rule base architecture

Fig.3 shows a simple flow chart how the rule base is designed in relation with our inference engine. It shows the overall process of how the information will be added and how the deducing of results will lead us to the final conclusions.

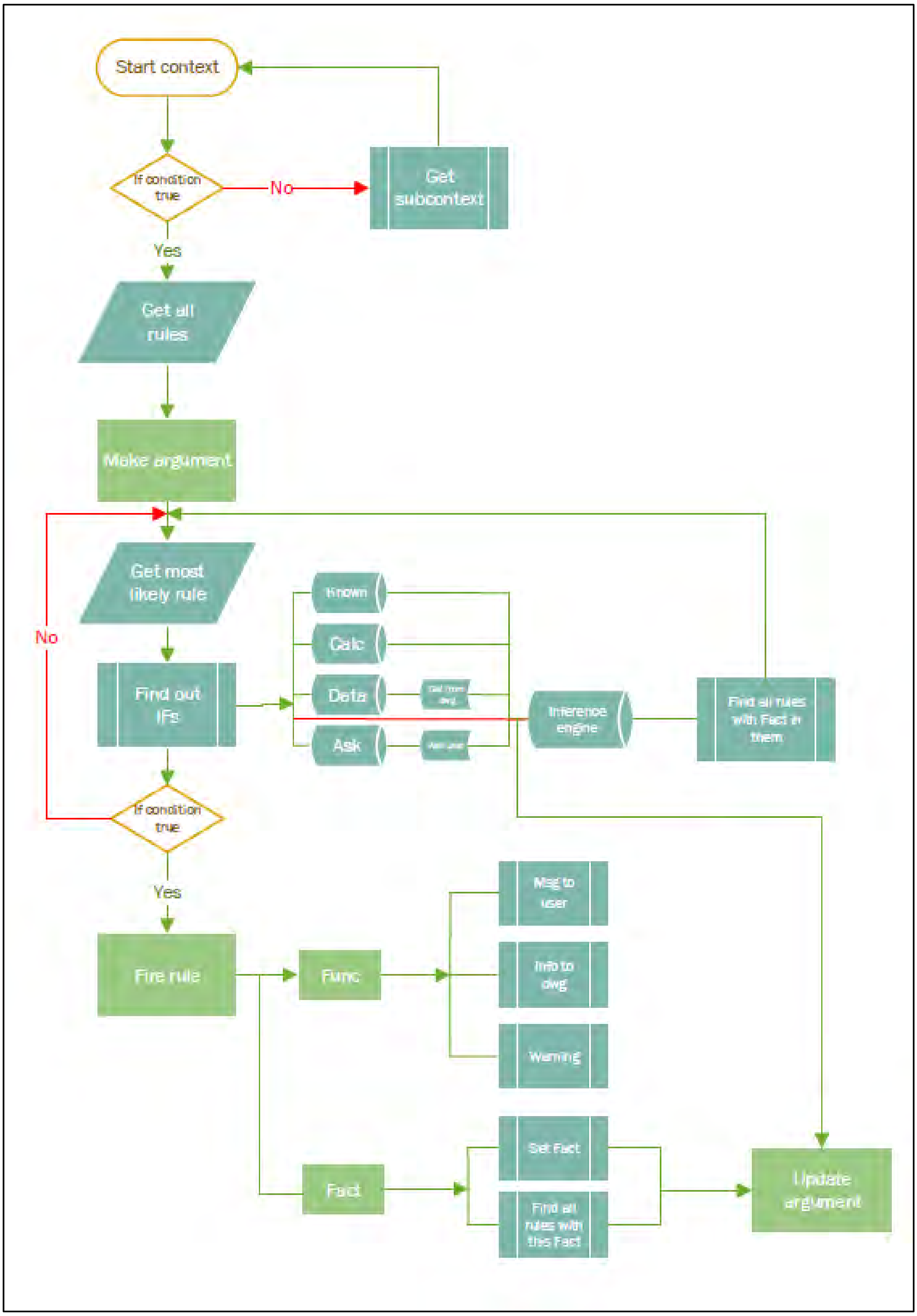

Fig.1: Proposed rule base and inference engine

6.1. The rules

Each rule consists of a number of parts:

```
DefRule R=Plate-MaxSize COMMENT: Check if max plate size is within
Yard limits
       IF: $OR Length > Yard.Plate-Max-Length
             Width > Yard.Plate-Max-Width
             THEN: 100 (Error Size in Plate $Id)
```

Name: Is a unique name that the Rule is referred by.
Comment: Is a short description of what this Rule does. It is used later on when an explanation for a certain decision is requested.
If: Is the collection of Facts that need to be True to make the Rule fire.
Cond: Is the relationship between the Facts of a Rule. This can be an $AND or $OR condition. If more complex situations are needed different Conditions need to be made part of the Inference Engine.
Then: Is the Conclusion of the Rule. In most cases it will conclude another Fact, like the state of a Plate, which indicates if it contains an Error. A conclusion has an associated Certainty Factor.
Facts: Are the Data elements of a Rule and can be part of the Premises (If) or the Conclusions (Then) or both. Since all Facts have an associated Certainty Factor, the Inference Engine needs a facility to combine the certainties of all its Facts.
Funct: The Conclusion of a Rule may also contain several Functions. In the example a text is written to a Log file and also to the Console. There may be a number of Functions on the System Level, like Messages, but also functions, associated with the Context level.

6.2. Certainty factors

To make reasoning with uncertainty possible, the Inference Engine needs some facility to handle this. There are several approaches to this; the most important ones are Bayesian Logic and Certainty Factors. They both combine the probability/certainty of all Facts of a Rule to a total Certainty when the Rule fires. For instance, if one of the Conditions of a rule has a very low certainty this should decrease the overall certainty of the conclusion. On the other hand, if there are several rules, that all can draw conclusions of a certain Fact, then each instance of such a Rule should increase or decrease the overall certainty. It should be some kind of majority ruling, that when two rules both conclude that something is True but another one that it is False, the total should be somewhat True but not False. This process is generally referred to as Truth-Maintenance.

6.3. Functions

In addition to drawing conclusions and determining the certainty of a Fact, Rules may also execute Functions. There can be a Message or a Log entry, but a Rule may also ask Questions or make Suggestions. In addition, a Rule might highlight the Plate on the screen, to indicate that something is wrong. If the system is used as a design assistant, there may be functions to redraw or resize one or more Plates automatically. Functions that otherwise would be done manually by the user could be automated by the rule base.

6.4. Knowledge base and inference engine

Knowledge base is implemented as an in-memory structure of all contexts, rules and concepts as defined in the source code for a certain Rule Base. It is entered with a standard text editor and compiled by Acquaint when loading the Rule Base. errors and warnings are generated for syntax errors, which need to be fixed before running the knowledge base.

7. Development environment

7.1. Development of instantiated Rule Base

Instantiation was originally thought to be realized by having many instances of a single rule. In the new Acquaint system, this has been implemented as Indexed Contexts, which act as a collection of Rules and Concepts, that may be re-used on different sets of input values. So there will always only be one set of active Rules in a given Context, but they can be re-used with different inputs and thus generated different outputs. Each case is handled completely throughout the entire Rule Base and when the final conclusions are drawn, a new case is started. If in the future, we will encounter situations that require several instances, we will set up a new mechanism to deal with that.

For instance, the current implementation will reason about a single plate. As explained earlier a plate is a construct, based on the boundaries of defined hull-lines on four sides. When one plate has been analyzed, the next one will be checked. However, when situations occur, where we need to reason about adjacent plates, there will be a need for two, or more plates. This can be solved initially by defining a number of separate contexts, one for each plate. If however there is a need for a variable or unlimited number of plates to co-exist, true instantiation will be required and we will need to adapt the Inference Engine.

7.2. Inference engine class

The actual Inference Engine and development environment is now based on Acquaint 2020, which is distributed as an executable and the Test Data Source, distributed as a Python program, later to be extended with the AutoCad interface, based on PyAutoCad.

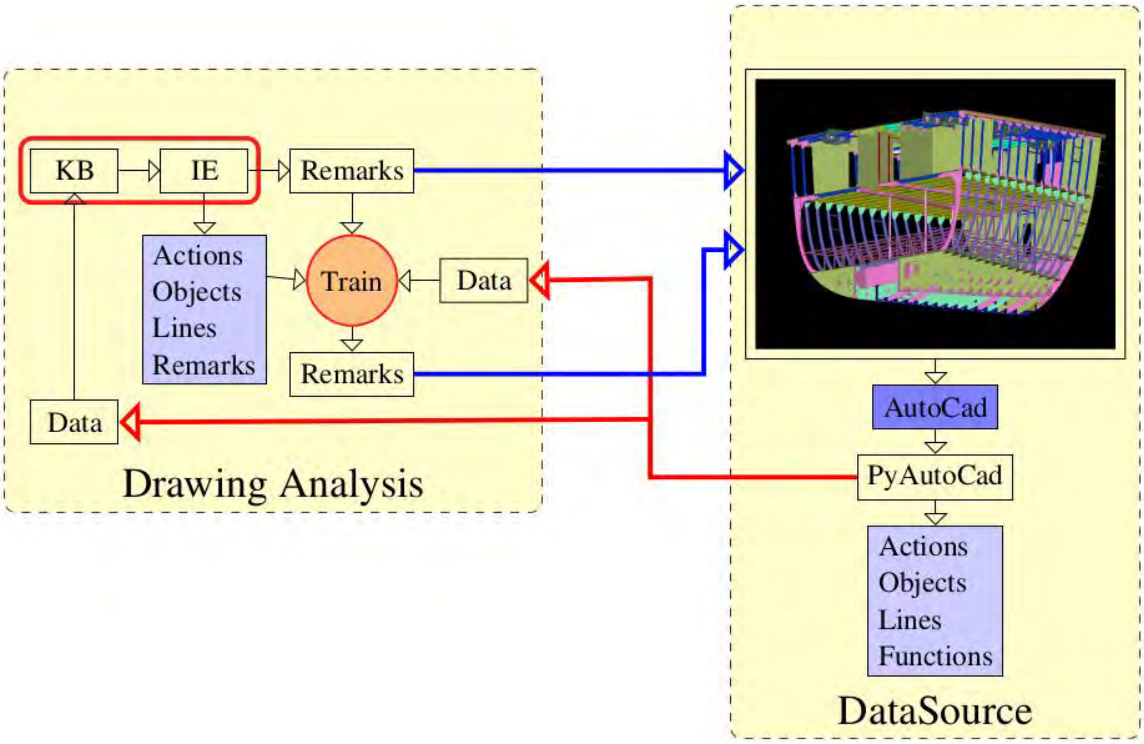

Fig.4: Inference engine class

7.3. Rule collection

Three example problems have been defined before and one of them has been implemented as a demo, domain, however, is still rather limited. What it currently does, is checking if a plate fits in the restrictions of a certain Yard. This is an example of relatively simple rules. They could be made more challenging, as can be seen in the Acquaint Demo system Spock, which is a simple Medical Diagnosis demo, dealing with children's diseases. The HullPlates demo could be extended with more complicated rules, if desired.

7.4. Acquaint: In-house testing facility

The development environment consists of a user interface, the compiler and the inference engine. They are provided as a installed python application that connects with the data source, when starting up. The data source can work independently, providing test cases as input, or be connected to autocad, once the pyautocad interface has been implemented.

When the system is disconnected from the data source, all data has to be entered by the user, providing an easy way to test the rulebase during development, as all information to be retrieved from the data source will be asked from the user. Underneath is an example of the user interface, operating without a data source. User face of such facility is presented in Fig.5.

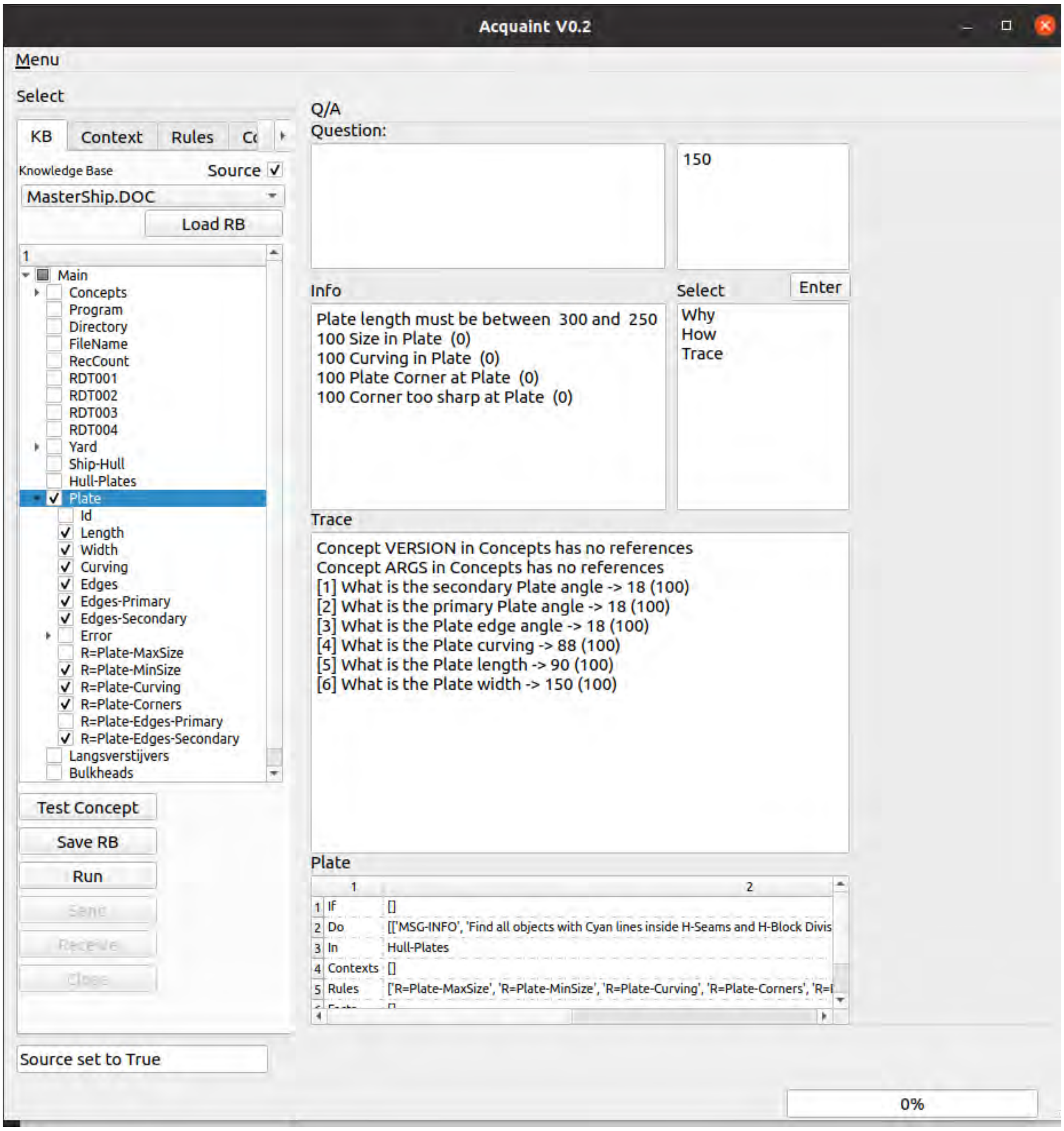

Fig.5: Acquaint user interface

7.5. Why acquaint?

Acquaint comes equipped with a learning facility in the form of Neural Networks. We intend to use this facility in the future as well. In general, learning requires a large number of examples and that is something, that is not available in our problem domain. That is the reason that a Rule Based system is much more appropriate for this problem domain than Machine Learning.

However, when using the system, many examples are gradually being collected. For the Ship-Hull example, for instance, each Plate represents a case, where the RuleBase provides an analysis, but it also offers an opportunity to collect data about each Hull-Plate that is being investigated. The learning interface can collect a number of properties about each hull-plate seen, and associate these with conclusions, drawn from it and feed this information into a Neural Network. That way we could also collect data about other elements, for which there exist no Rules yet. The learning mechanism will be able to collect information in this way and 'learns' new rules, that are not based on the If-Then format, but on the association between properties, thus forming a new 'Neural Rule', that collects more knowledge as the system is being used.

This learning facility will be part of a future version of Acquaint and it will be to our advantage to think about the possibilities in advance, in order to make it part of the total approach.

8. Conclusion

During this feasibility we have implemented our previous findings in-compliance with our testing facility environment and we succeeded to deduce many interesting facts. Based on these facts we can further expand our project scope area. The main findings of the study are the following:

1. Artificial intelligence in the field of ship construction will not only solve the long-standing issues of mankind in the engineering process but also expand the scope into new heights.
2. From technical perspective, we realized that there are several open-source and commercial Inference Engines available, the ones most useful for this project are written in Java which implements some dialect of Lisp.
3. Using such a system requires the development of a two-way interface between Auto-CAD and the Inference Engine. After trying to use one of the existing interfaces it became clear that the amount of work to make such an interface work seems larger than the effort to build the Inference Engine itself. None of the available interfaces we found, were in use, nor were they maintained and that is not without a reason.
4. The complexity of the Inference Engine for this project is actually not too large, because most of the problems need to be solved in interfaces between the Rule Base and AutoCAD. Certainly in the beginning a simple forward chaining approach is sufficient and we found some open-source projects that could serve a good starting point.

The kind of Rules that would be required for the desired KBE were investigated by building a mock-up Rule Base for three small example projects. In some cases, it proves that a more tightly integration between the required AutoCAD functions and the Rule Base could benefit, which is another reason why a dedicated Inference Engine would be more appropriate

9. Recommendations

Based on these findings, backed by some implementations of parts that seemed most crucial we recommend the following plan of action:

1. Finish the demo project and develop a working Rule Base for the ShipHull example. This requires completing the AutoCAD interfaces.
2. Build a very small first Inference Engine, which does nothing else but execute the Rules sequentially. If forms the basis for further development.

3. Make this first demonstration work completely and use as a basis for the development of a Proof-Of-Concept project.
4. Set up a plan to extend this demonstration into a full POC in which the three main components, the Rule Base, the Inference Engine and the AutoCAD interfaces are implemented and form a basis for further development.

We can overall conclude that at this stage we may further need to inspect the rule base tree by expanding the main items of the test facility. It is unstable and selecting things may crash the system Please note that there is a timeout on answering questions, Currently if you do not answer in time, it crashes which leads us to investigate further to this testing environment to make it stable and effective.

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Scheduling and Visualization of Acceptance Tests and their Dependencies for an Augmented Reality-based Commissioning Assistance System

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Abstract

The constant need for higher productivity in the shipbuilding sector leads to an increasing motivation for digitalization of manufacturing and commissioning processes. Nowadays, commissioning plans consist of numerous interdependent acceptance tests whose dependencies are only implicitly represented. A holistic digital commissioning application should facilitate the creation, execution and documentation of tests. For this purpose, an existing augmented reality-based assistance system toolkit was extended to allow for creation of functional and scheduling dependencies between acceptance tests using an interactive and graphical interface. The resulting commissioning schedule is linked to a digital twin, which contains all necessary information for execution and documentation.

1. Introduction

The commissioning of partial and complete systems is one of the key processes in maritime one-off production, as successful acceptance is a prerequisite for payment of an order. During commissioning, the views of the shipyard and the operator meet for the first time in the life cycle of the product. Therefore, relevant data are transformed from a production-based structure to a structure which is oriented towards ship operation.

In order to provide data in a common form, steps are being taken in many industries towards a digital twin, which is defined as a digital representation of objects from the real world, *GI (2018)*, that encompasses the entire life cycle and contains not only data but also, for example, models of plant behavior.

For the digital twin of a ship, the needs of different stakeholders in regard of information acquisition must be taken into account. After an internal check by the quality management department, a transition in the commissioning process takes place to involve the shipyard, the client, and the classification society. Moreover, the digital twin should also reflect relevant acceptance processes at the supplier, and provide operational data for the client in a simple manner. During operation of the ship, the digital twin can filter logged data of systems in order to generate important information which can be used as a basis for potential retrofit in the future.

For maintenance, repair and retrofit, a digital twin has already been developed in a previous project, *Meluzov et al. (2020)*. It forms the data basis of a digital assistance system that supports service technicians and on-board personnel and is further linked to maintenance order processing, maintenance history and spare parts management by IT integration. Support for case processing and simple generation of maintenance instructions both are crucial for cost-effective use.

In this paper, it will be shown which additional requirements are derived from the analysis of the commissioning execution process and the authoring process of commissioning plans, and their related documents. The requirements serve as a basis for defining the necessary functionalities for authoring acceptance tests, which are presented to the commissioning engineer on board via a mobile digital assistant system during commissioning execution.

2. Fundamentals

Acceptance protocols, similar to maintenance instructions, represent work plans for the components located in the structural bill of material (BOM) and the 3D geometry models. These work plans contain a description of the task to be performed in addition to meta-information and attributes. The requirements of maritime commissioning are analyzed in the following section to determine which functionalities are needed to extend the existing maintenance assistance system.

2.1. Requirements of Modern Commissioning

During the commissioning of ships, there is an enormous number of tests that must be passed for a successful handover to the customer. The creation of the acceptance tests and the associated reports is therefore a time-consuming process. The requirement for modern commissioning is to accelerate and optimize this creation process by means of data-supported assistance systems. Documents from past commissionings can form the necessary basis for this. Commissioning planning must also take into account that the tests are interconnected via a complex mesh of dependencies. These can be sequential, meaning that a test has one or more necessary predecessor tests. But there is also the important case of synchronous, cross-trade dependencies, where several trades are involved in an acceptance test at the same time, but often at different locations. In order to carry out a commissioning as quickly and reliably as possible, it is therefore necessary to carefully determine the dependencies between the tests. In modern commissioning, these should be derived automatically, for example from hierarchically structured bills of materials in which the components are assigned to the assemblies, *Kummer (2019)*, or from schedules of past commissionings. The latter can be achieved e.g. via identical start times or special keywords. Subsequently, the generated results should be validated by experienced employees and corrected if necessary.

In order to remain competitive and to realize the shortest possible delivery times for the customer, commissioning nowadays takes place partly in parallel to the construction phase of the ship. Tight, yet reliable scheduling of commissioning is therefore becoming increasingly important. In addition to the dependencies, various other information must be obtained and taken into account, such as the expected processing times, predefined commissioning milestones, the assembly schedule, resource availabilities and disturbance factors. Processing times are often specified on the basis of experience or via standard values. A more contemporary approach, on the other hand, would be to calculate processing times automatically on the basis of past schedules. In addition, in order not to violate any of the above-mentioned factors in scheduling, modern assistance systems should be able to automatically generate appropriate scheduling suggestions for commissioning, or check manual entries for feasibility. Here, the current status of commissioning and assembly should also be taken into account, and the accuracy of the dates should be increased in the progress of commissioning, so that ultimately sea trials are timed to the minute.

To ensure that data from past commissionings can be optimally used, as described above, it should already be available in a compatible, standardized form. Therefore, a modern approach has to move away from isolated software solutions such as Excel, MS Project or special "flat" commissioning systems, each with different data structures. Instead, the goal is to create an integrated system with a central, linked database which acts as a digital twin for the whole process.

In the field of building management, this approach is already widespread under the term "Building Information Modeling" (BIM), but this requirement is also increasingly coming into focus in the shipbuilding industry, *Luming (2015), Boton (2018)*. The advantage of using historical data lies in learning from own experience in the long term and not having to reacquire the knowledge for each commissioning. This can be achieved by methods of machine learning so that modern organizations would improve their processes with each new ship.

Despite the opportunities offered by automated determination of planning data for commissioning projects, a human expert will still need to ultimately have to take the important decisions. For this reason, an assistance system is needed which can present large and complex data clearly, and enable intuitive interaction. Modern approaches lean towards linking different visualization methods, such as 2D and 3D geometries, together with diagrams and tables. The advantage of using 3D geometries comes into effect throughout the planning phase, as well as in the execution phase. Especially during the execution phase, commissioning engineers can utilize augmented reality to quickly identify acceptance tests and steps on site, and to display relevant additional information directly linked to real objects.

2.2.1 Digital Information Assistant (DIA)

The commissioning system proposed in this paper uses and extends the infrastructure for digital information assistance (DIA) systems developed at the Institute of Production Management and Technology (IPMT), *Meluzov et al. (2019)*. The DIA application was first developed by Halata for one-of-a-kind production, *Halata et al. (2014),* and was later upgraded to be deployed in maritime maintenance, *Meluzov et al. (2020)*. The DIA infrastructure consists of three main modules:

- <u>Creator</u>: responsible for service instruction authoring
- <u>Director</u>: used for project management and documentation
- <u>Visualizer</u>: an augmented reality-based mobile application used for assisting maintenance workers by visualizing service instructions.

In addition to the above mentioned three modules, other secondary modules exist as shown in Fig.1.

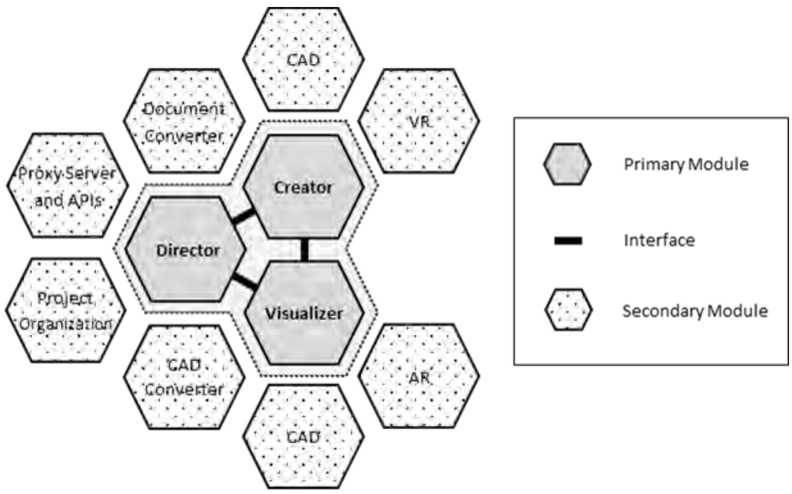

Fig.1: DIA structure

The significant functionalities provided by the DIA system can be categorized according to the phases of maintenance defined by Meluzov et al. (2019). During the execution phase, mainly the visualizer application is used to provide maintenance workers with all the information required for executing their tasks. For example, desired values and set points, tools to be used for maintenance, and important hints and warnings. Using the visualizer application, workers can perform their tasks and report feedback as well as set values for documentation purposes.

Documentation is then done by means of the director application, which also provides a database for archiving all the maintenance data. The director generates maintenance reports to be used by clients and product owners. Furthermore, any technical features concerning CAD data handling, such as format conversion, and IT interfaces for data transfer are provided by the director application. One of the significant functionalities provided by the director is the automatic generation of service instructions by processing technical documents and datasheets. Such functionality saves much of the authoring effort.

However, the authoring process can be more complex and therefore a dedicated creator application was developed. The creator is an application used mainly for creating animated virtual instructions that are subsequently transferred to the visualizer application. The virtual instructions can be created either on a desktop computer or by using a virtual reality headset. The VR creator handles the cases of service instructions that require complex animation. Moreover, the VR creator can also be used for training maintenance personnel, *Friedewald et al. (2019)*.

2.2.2 DIA Extension: Commissioning Functionalities

Due to the modular design, the DIA system could be extended with manageable effort for maritime commissioning. The following list shows the most significant commissioning functionalities added to the DIA system, while maintaining the basic structure consisting of the director, creator and visualizer:

- Generation of hierarchical dependencies: automatic generation of dependencies between acceptance tests according to the hierarchy of structural bill of materials.
- Generation of parallel dependencies: automatic generation of dependencies between acceptance tests belonging to systems of different trades. The automatic generation is based on past commissioning schedules.
- Generation of commissioning schedules: automatic generation of commissioning schedules based on their dependencies, while taking into account past commissioning schedules as input.
- Visualization of hierarchical and parallel dependencies: providing an overview of existing acceptance tests and their dependencies, whether hierarchical or parallel. The visualization has different modes, such as 2D and 3D visualization. Moreover, the visualization process takes the commissioning schedule into account.

The functionalities listed above are discussed in detail in the next chapters.

3. Scheduling in Maritime Commissioning

In order to create the commissioning schedule, two main steps are necessary, which are described in the following two sections. In the first step, functional dependencies are determined in order to derive the mandatory sequence of commissioning tests. After this step, there is still freedom in the sequence design, since not all commissioning tests are functionally dependent on each other. In addition, no dates have been set yet. This is done in the second step of scheduling, where the individual dates within the milestone plan are determined.

3.1. Acceptance Test Dependencies

Acceptance tests are performed in a specific sequence that is determined according to factors such as dependencies and resource availability. Dependencies between the acceptance tests result from constraints, which can be either technical or organizational. If those constraints are of technical kind, the resulting dependencies between the acceptance tests are referred to as functional dependencies. In this paper, functional dependencies are further classified according to their location into hierarchical and cross-trade dependencies.

3.1.1 Generation of Hierarchical Dependencies

The hierarchical structure of the system to be commissioned can predetermine the execution sequence of its acceptance tests. Sub-components inside a system usually need to be tested before the overall system can be commissioned. Therefore, the hierarchical structure can be used to automatically derive an execution sequence of the acceptance tests within a single system. However, it is also useful to utilize the hierarchy structure to automatically generate acceptance test specifications rather than just their sequence of execution.

The commissioning system presented in this paper uses the structural BOM and the 3D CAD models of the components in the ship to determine hierarchical dependencies. Structural BOMs and 3D models have a tree structure by default which defines the hierarchy of the system. A hierarchical dependency generation algorithm parses the structural BOM's tree representation from top to bottom and detects relevant acceptance tests. The acceptance tests are then sorted in an ascending order to create a commissioning sequence.

However, in order to automatically detect the associated acceptance tests, additional information is required. The algorithm discussed here, which is implemented by the digital twin, uses commissioning schedules to filter out commissioning-relevant objects from the 3D CAD models. The following figure shows the steps for generating the hierarchical dependencies from 3D CAD models with the help of past commissioning schedules:

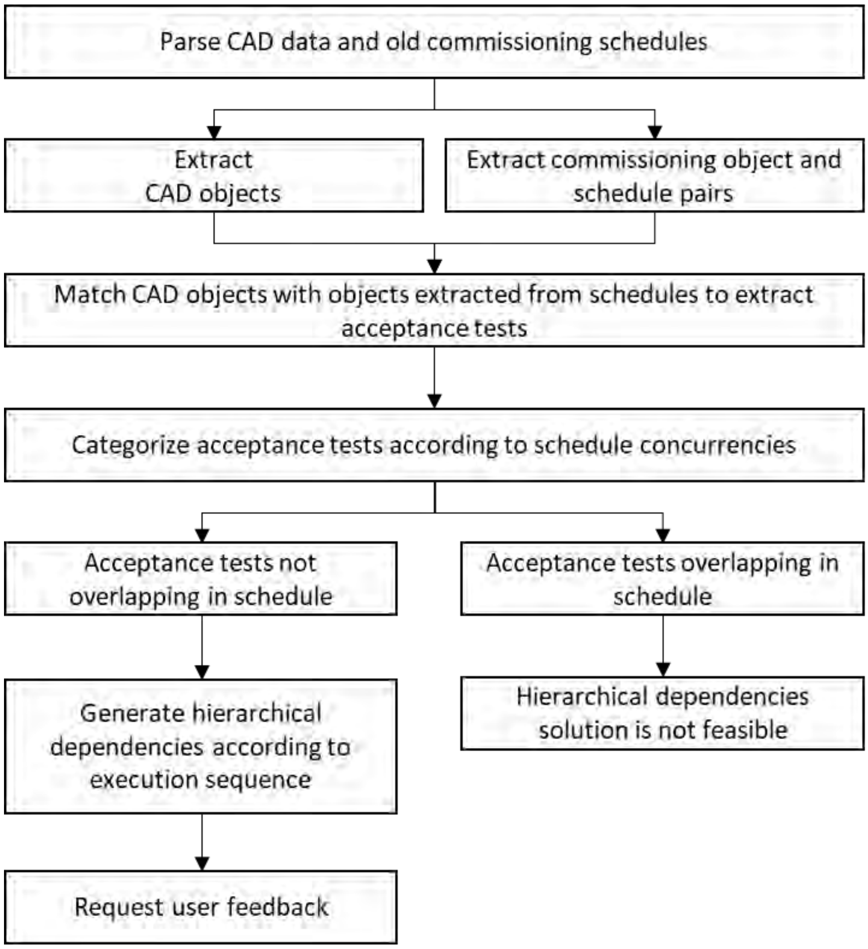

Fig.2: Automatic generation of hierarchical dependencies

Fig.2 shows that the hierarchical dependencies are generated according to the sequence of execution of the acceptance tests. Sequential execution indicates a probability of having a dependency between the tests because otherwise they could have been executed in parallel. This assumption can lead to mistakes, and therefore, manual human feedback is required. The feedback step is necessary to train the algorithm and to optimize the processing accuracy of the digital twin. However, the second case of overlapping acceptance tests in schedule is more complex to handle. This case is discussed in the next section. The detailed operation contents of the commissioning plans can be extracted from existing plans that have already been successfully executed, or they can be derived from the relevant regulations, e.g. DNV or VDE guidelines for specific components. These aspects will not be discussed in detail here.

3.1.2 Generation of Cross-Trade Dependencies

If the commissioning schedule contains acceptance tests executed in parallel, this may indicate either resource saving reasons or that the tests must run in parallel, i.e., there is a parallel dependency. Parallel dependencies are referred to as "cross-trade dependencies" in this paper. The term is mainly used to describe dependencies between acceptance tests that are performed on systems requiring expertise of different trades. For example, tests that require the expertise of commissioning engineers from electrical and mechanical engineering trades. The automatic classification and detection of cross-trade dependencies is crucial for efficient resource and schedule planning, as well as for better coordination and collaboration between the personnel of different trades during the commissioning execution. In order to determine whether cross-trade dependencies do exist for individual ship systems, existing acceptance plans must be reviewed. Fig.2 shows that the acceptance tests which are overlapping cannot be used for generating hierarchical dependencies. Therefore, the algorithm in Fig.2 is further extended to handle the case of overlapping acceptance tests. The following figure shows the different possible cases of overlapping acceptance tests:

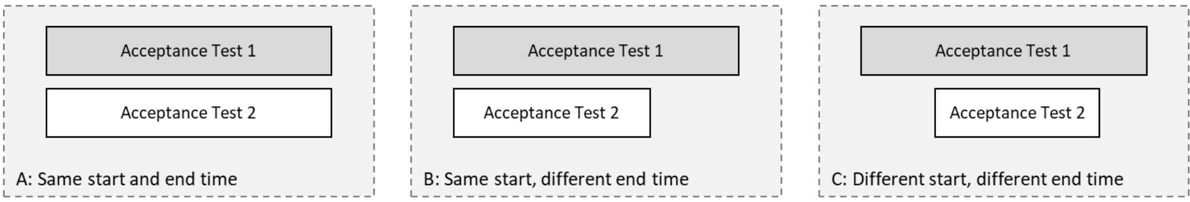

Fig.3: Overlapping cases in commissioning schedules

Fig.3 shows the three main cases that the dependency generation algorithm takes into account. Case A, is the most prominent criteria that two acceptance tests may have a cross-trade dependency. The fact that both tests started and ended at the same time indicates that they must have run in parallel and that resources from different trades must have been allocated for the execution period. Case B is where both acceptance tests only share the start time. This case is handled using a tolerance value, meaning that if the end time varies within a certain percentage, a decision is made by the algorithm whether to consider both acceptance tests as dependent. The third and last case C is where acceptance tests differ in both start and end times. In that case, the algorithm does not consider the acceptance tests to be dependent.

So far, the algorithm considered the start and end time as the main attributes for recognizing cross-trade dependencies. Further secondary attributes are also considered, for example resource allocation and any keywords which may indicate dependencies between the acceptance tests. It is worth noting that a final feedback step from the user is still required to detect mistakes in classification and to further improve the efficiency of the algorithm.

3.2 Scheduling of Acceptance Tests

By defining the functional dependencies between the acceptance tests (see section 3.1), the mandatory sequence of acceptance tests is determined. This section describes how these tests are subsequently scheduled first roughly and later in detail. Fig.4 shows the process flow diagram for this sequence, which is described in more detail below.

For rough scheduling, it is important to know the required processing time of the acceptance tests. In order to reduce manual entries, these are automatically estimated based on past commissioning projects. For this purpose, past schedules of comparable ship projects are analyzed by the digital twin and the average processing time of comparable acceptance tests is calculated.

Another important source of information for scheduling is the commissioning milestone plan, which can be generated from the project plan. The milestones form the basic framework for scheduling, since a large number of the tests can only be carried out in certain phases between the milestones. The installation schedule is also of great importance for scheduling, since commissioning can naturally only take place after the installation has been completed. If the installation schedule is not available, backward scheduling must be done based on the milestone schedule.

Based on the mandatory sequence, the processing times of the acceptance tests, the milestone plan and, if applicable, the schedule of installations, a rough, automatic scheduling of the commissioning takes place. For this purpose, the logic from the network planning technique is used, *Noosten (2013)*, which also results in the critical path. The result and the correlations can be viewed by the user in the application and adjusted if necessary.

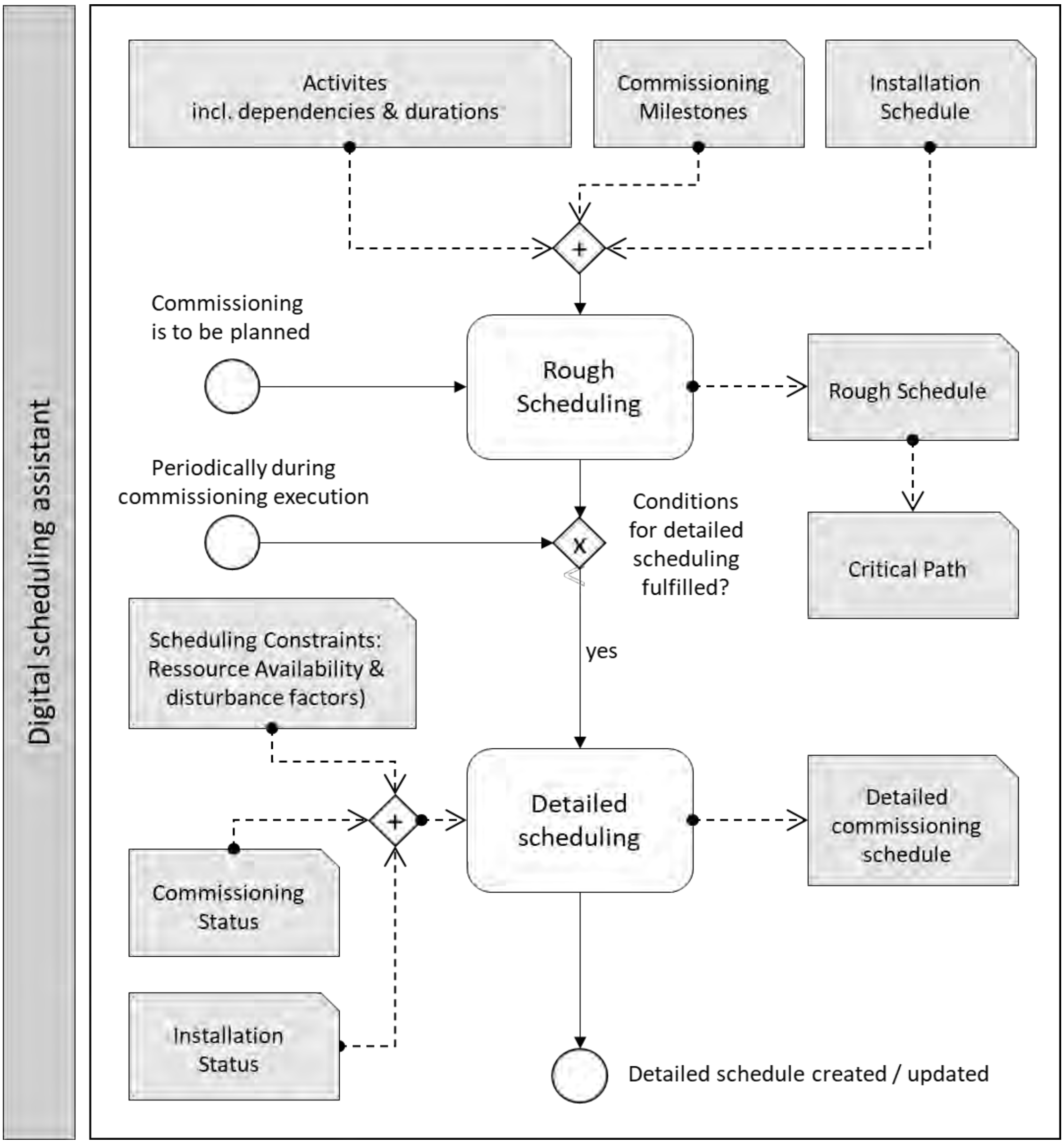

Fig.4: General scheduling process flow diagram

During commissioning, relevant boundary conditions often change, for example due to schedule delays. Therefore, it is reasonable to define the exact time of the acceptance tests only a few weeks to days before their execution. In order to take this into account in the developed algorithm, conditions can be defined under which detailed planning can take place. These can be, for example, meeting a defined deadline or the completion of the predecessor tests. Once detailed scheduling has been triggered, the status of commissioning and installation are checked to automatically determine the earliest possible start date for the acceptance tests. Subsequently, the exact dates can be determined by taking into account the scheduling constraints. For this purpose the application provides suitable suggestions, which the user can adjust as required. Section 4.3 describes this process in more detail. Investigations within the scope of this paper showed that the resource availability and disturbance factors in particular must be taken into account in order to determine suitable time windows. Both can be further subdivided as following:

Resource Availability

- Participants
- Tools
- Location
- Utilities

Disturbance Factors

- Commissioning Activities
- Production Activities
- Environment

Participants can be internal specialists as well as external persons such as subcontractors, the customer and the classification society. Utilities are, for example, electrical power or cooling water. The location is also a limited resource, as it can be blocked by other activities running in parallel. Availability for all resources must be ensured when determining the exact start and end date.

In addition to resource availability, disturbance factors are the second important constraint to be checked. Disturbances can occur, e.g., due to parallel commissioning activities or installation work, such as noise, dust or vibrations. But environmental influences, such as the time of day and related lighting conditions and, last but not least, the weather, can also disrupt commissioning and must therefore be taken into account when detailed scheduling is done. Considering resource availability and the relevant disturbance factors, the application determines appropriate time intervals for the activities within which the user can select the exact date. Sections 4.3 describes the visualization of this process.

4. Visualization

As *Halata (2014)* has already stated, an adapted visualization facilitates human information processing in a decisive way. That is why special attention was paid to an optimal visualization form of the commissioning content during the development of the application introduced in this paper as well. The following section shows which visualization approaches were used for the development of the application and how these were actually implemented for the various requirements in order to achieve optimal user guidance.

4.1. General Visualization Requirements

The goal of the developed application is to improve the performance of commissioning management. To achieve this, the approach of visual management was used. This approach includes the use of visualization devices to provide the user with high quality information. This means that the information displayed is necessary, relevant, correct, immediate, easy-to-understand and stimulating. Thus, the organizational context can be grasped at a glance, *Tetzel (2009)*.

To realize relevant and immediate representation of information in the commissioning system, the user interface was divided into three main panels that adapt to different working modes. The left panel extends from the very top to the bottom of the screen and is used for displaying and editing textual information of the acceptance tests and their milestones. The upper right panel contains a geometry view, which is intended for displaying and interacting with both 2D and 3D content. The lower right panel contains views for editing the dependencies and the time schedule of the acceptance tests.

It is worth noting that the three panels are reactive in the sense that they respond to any filtering triggers. For example, selecting one acceptance test from the dependency view triggers a change in the geometry view to display the location of the clicked acceptance test. This omits any cluttering of information and provides a clear view of information. The following sections explain the most significant visualization modes in detail.

4.2 Geometry View

Authoring augmented reality content requires an environment in which the planning engineer is able to interact with 2D and 3D objects. Therefore, the geometry view was created in the commissioning system. The AR authoring starts with assigning an acceptance test to its corresponding object, or setting the coarse location on a 2D map of the ship. Authoring for AR-based assistance systems has been successfully used in the DIA maintenance system, *Meluzov et al. (2019).* The benefit of using 3D is being able to locate difficult components that are not to be found easily during the commissioning process, for example sensors hidden behind surfaces or walls.

Another significant use of the geometry view is to provide an alternative view of acceptance test dependencies. In a large commissioning program, it can be difficult to get an overview of the dependencies of the acceptance tests. Therefore, representing the dependencies on a map, or a 3D model, can be more intuitive. However, the benefit of such representation is maximized even more when the filter functionalities provided by the geometry view are used.

A filter functionality is implemented to allow the user to filter for various attributes, such as assembly groups, schedule, and disturbance factors, to obtain a prognosis of acceptance tests that might fall out of schedule. The geometry view would then highlight the areas of the ship that are behind schedule and suggest alternative solutions, *Heinig (2015)*. Detecting any deviations in the commissioning plan is performed by a digital twin monitoring the entire commissioning process. The following sections will show different examples and use cases of the geometry view.

4.2 Visualization of Hierarchical and Parallel Dependencies

Knowing that a single commissioning may contain over ten thousand acceptance tests, obtaining an overview of all the tests and their dependencies can be a challenge. Therefore, a visualization approach was developed to overcome such demanding task, if the dependencies cannot be derived automatically from existing data. The visualization approach takes into account the type of dependencies between the acceptance tests to provide a suitable visualization method. In this section, two methods of visualization are shown: hierarchical dependency and parallel dependency visualization. Hierarchical dependency visualization is used for acceptance tests of a single system. For example, a cooling system whose acceptance tests are organized in a hierarchical manner where the first test is performed at the bottom of the hierarchy. Fig.5 shows the hierarchical dependency view.

In the hierarchical dependency view, the acceptance tests are organized from bottom to top (left to right) according to the structural bill of material. Tests belonging to the same hierarchy are represented below each other, which indicates that they can be performed in parallel, if they are not dependent on other tests in a different hierarchy. A color code is used to label the tests according to their level in the hierarchy. The darker the color, the higher the test is in the hierarchy. The blue color indicates acceptance tests belonging to the hydraulic assembly group. Color codes can be re-configured if required.

In the case of a complex hierarchy, the color codes can also be reflected on 3D geometries. Using such an approach provides the user with an alternative visualization of hierarchical dependencies by representing the dependencies spatially and allowing the design engineer to edit the dependencies directly on the corresponding 3D objects.

Fig.5 focuses on a single system, represented by “Acceptance Test 6”. However, it is possible that there exist parallel dependencies spanning across different systems, as explained in section 3.1.1. In this case, parallel dependency view can be activated to indicate the necessity of two tests running in parallel. The following figure shows the corresponding parallel dependency view:

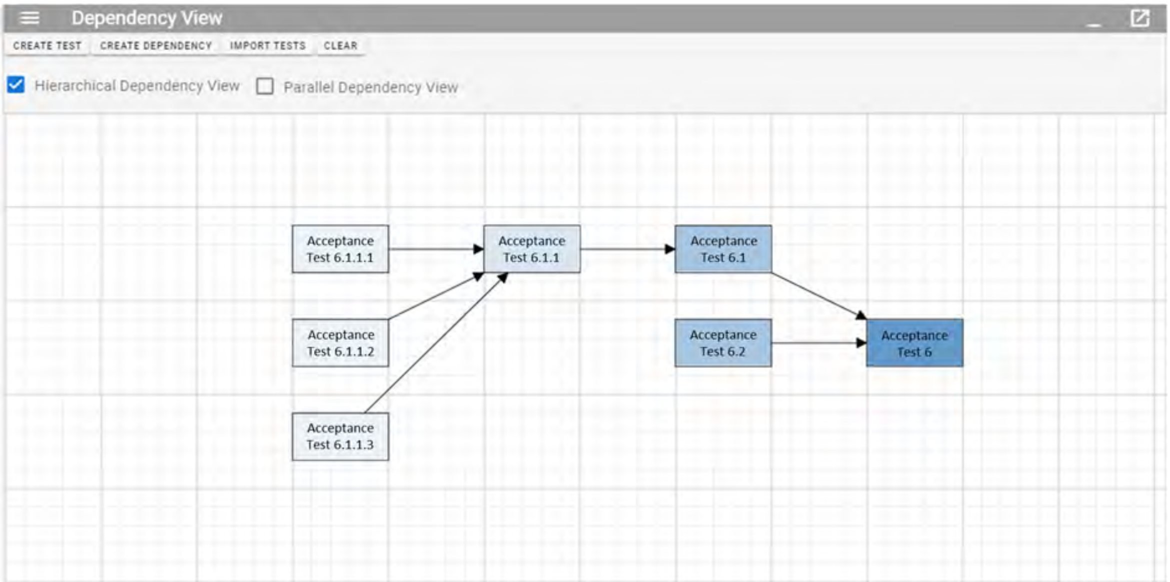

Fig.5: Hierarchical dependency view

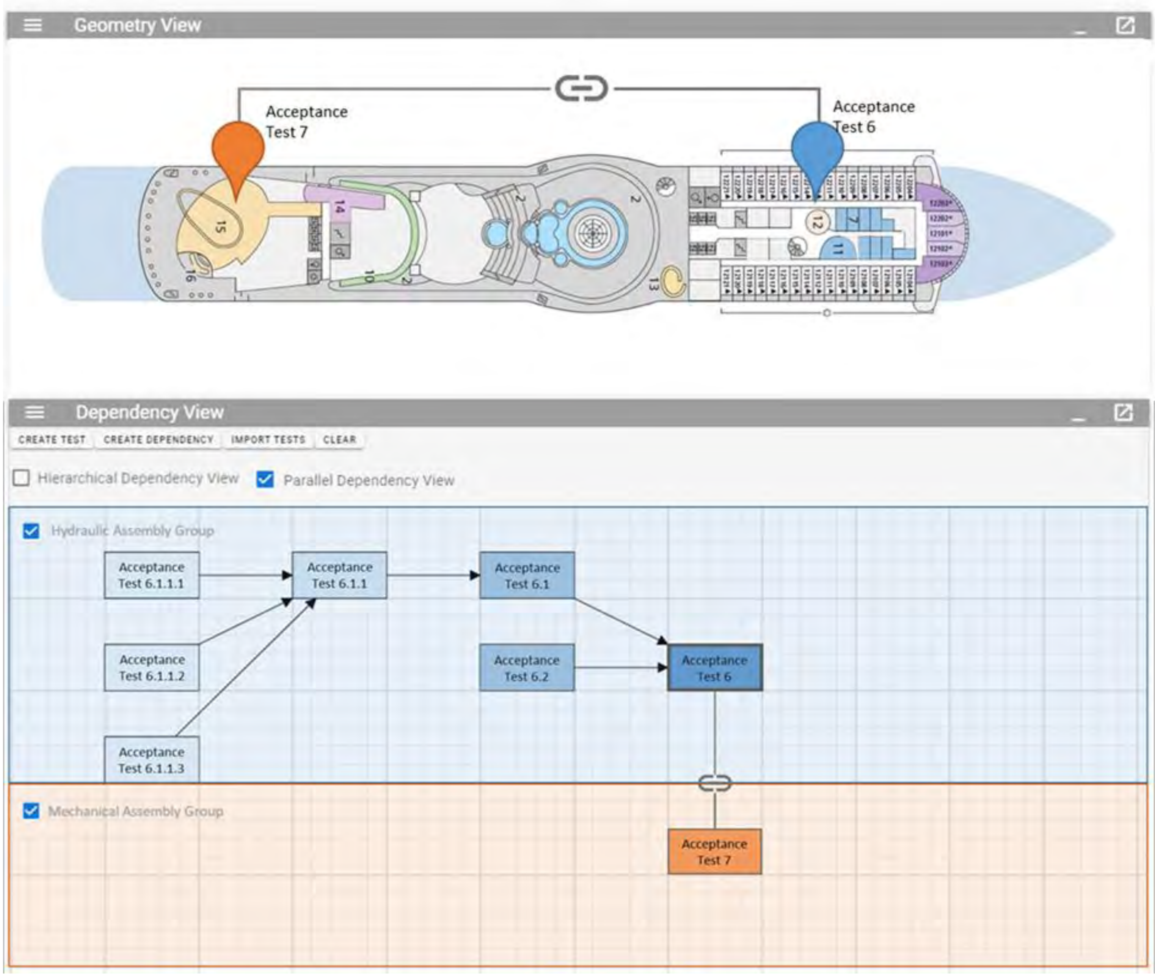

Fig.6: Parallel dependency view

Acceptance tests which have a parallel dependency are connected together via a link icon. Clicking the link icon shows additional information regarding the different trades involved in the interdependent acceptance tests. The figure shows also a 2D view of a ship deck on which both tests take place. This is helpful for coordination between commissioning engineers that are performing the acceptance tests. Furthermore, the 2D view can be switched to a 3D view, if a corresponding 3D model exists.

4.3 Visualization of Detailed Scheduling

As described in section 3.2, the application supports the user in various tasks of the scheduling process. These include, in particular, the partially automated creation of rough schedules and the determination of suitable time windows for manual detailed scheduling.

In order to optimally support detailed scheduling, the user interface of the scheduling wizard was structured in such a way that the user sees all relevant information for scheduling the tests in an overview, see Fig.7. This includes especially the resource availabilities as well as sources of disturbances.

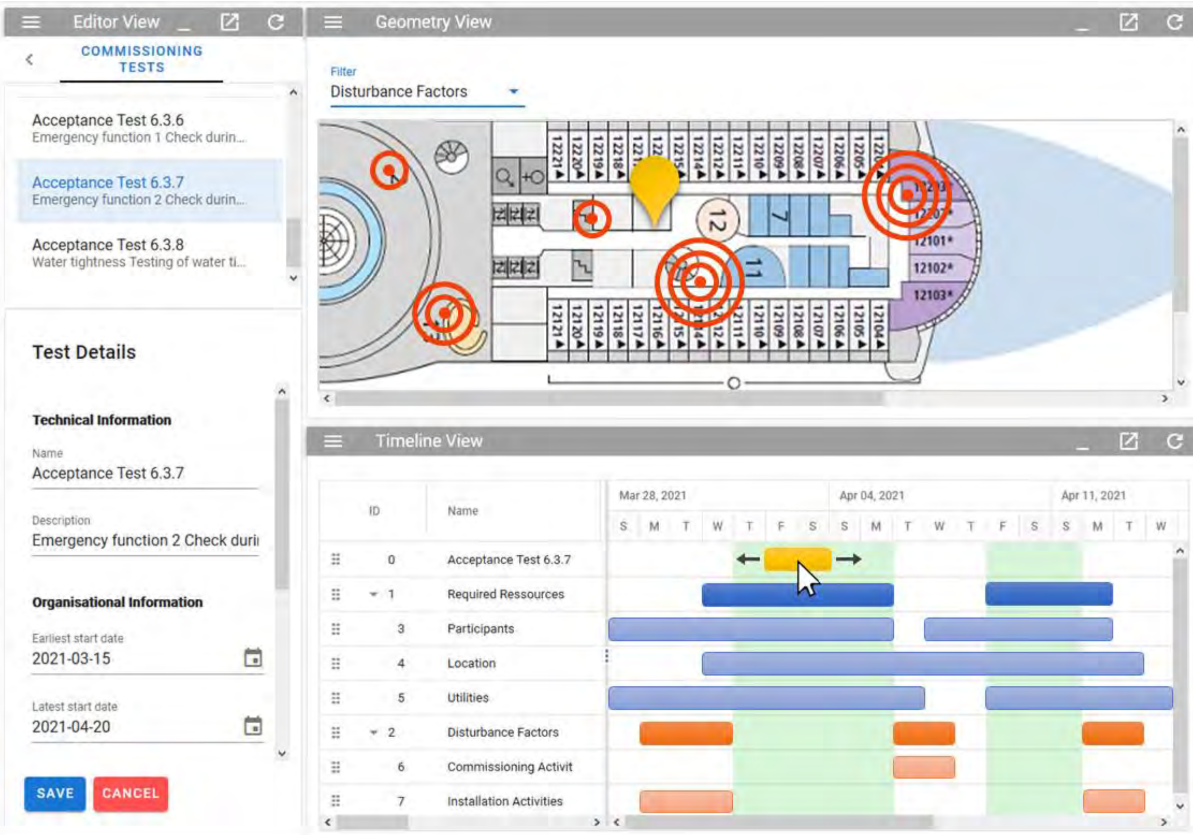

Fig.7: Detailed scheduling

In the editor view on the left, technical and organizational information about the inspection is displayed in order to be able to grasp the context of the inspection in relation to the entire commissioning at a glance.

For the spatial classification of the inspection in the overall context of the ship, a 2D or 3D model of the ship is displayed in the upper Geometry View. In addition to the test to be scheduled, potential sources of interference are visualized. The interference sources can be caused by commissioning or installation activities or by environmental influences (see section 3.2). The intensity of the interference is symbolically illustrated by the size of the icon. In addition, to meet the visual management function of "simplification", *Tetzel (2009)*, the system automatically zooms in on the relevant area in the ship, i.e. only tests and sources of interference that form a relevant influence are in the field of view.

The timeline in the lower area serves to link this spatial information with the temporal dimension. In this view, the presence of the disturbance factors as well as the availability of relevant resources is plotted. By expanding and collapsing the resources or disruptive factors, the more detailed subcategories below can be shown or hidden. The displayed time interval is determined on the basis of the rough scheduling, taking into account the current commissioning and installation status, and the resulting earliest start and latest end time, compare section 3.2. Time ranges in which all required resources are available as well as no disturbances are to be expected and which have a specifiable minimum length are highlighted in green. The user can now intuitively move the test to be scheduled along the timeline via drag and drop inputs. The view in the upper geometry dynamically adapts so that the interference sources active at the time are displayed.

4.5 Outlook: Commissioning with the AR-based Mobile Digital Assistance System

For the execution of the commissioning, the individual activities and the required resources are displayed on the mobile digital assistance system, Fig.8, which serves as the visualizer component of the overall system, refer to section 2.2.1. Also the assistance system supports in reporting confirmations, values or open points, etc. in order to generate acceptance protocols, or to initiate suitable remedial measures. In addition to the attribute enrichment presented by *Meluzov (2020)*, automatic data transfer from the affected ship systems will be implemented where useful and possible.

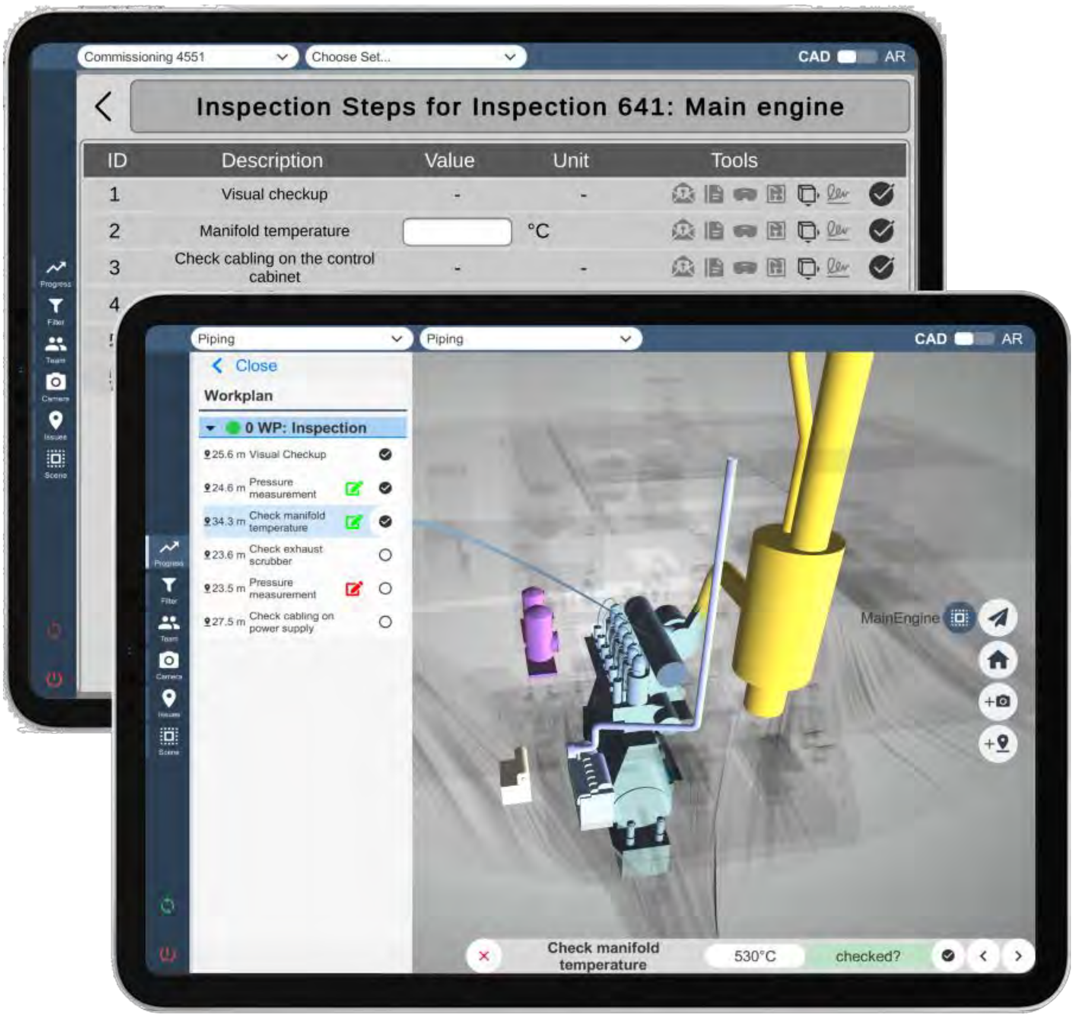

Fig.8: Preview of the commissioning with a mobile assistant systems

As shown in section 3.1, acceptance tests involving several trades at the same time are an important special case. When planning these commissioning activities, it is important to ensure that all relevant resources are available at the same time and that all tests involved are scheduled at the same time.

When it comes to use on board, a mobile assistance system will support execution, communication and coordination between the trades. To achieve this, the commissioning engineer can see not only his own commissioning steps, but also those activities of other trades which are running in parallel and which they depend on. The coordination is facilitated by the digital twin, to which the overall status is reported.

Subsequently the digital twin delivers all relevant status messages to the parties involved (also at different locations on the ship) and thus indicates the next open action in each case.

To pinpoint problems arising from the surrounding activities (possible disturbing activities of other nearby trades), spatial visualization of the environment is helpful. For this purpose, the current activities can be additionally displayed in a CAD or augmented reality view. The described functionalities ensure that dependent steps are processed in the correct sequence by all trades with low effort.

6. Conclusion and Future Works

To enhance the planning process of maritime commissioning, an existing digital assistance system (DIA) was extended to enable the authoring and scheduling of acceptance tests and their dependencies in a graphical and interactive way. The developed system relies on past commissioning plans and spatial information, represented by 2D and 3D geometrical data, to automatically generate hierarchical and cross-trade dependencies, as well as the corresponding commissioning schedule. Moreover, the developed functionalities form a basis for the ongoing development of an augmented reality-based mobile digital assistant that should facilitate commissioning execution.

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Improved Arctic e-Navigation by Using Earth Observation Products

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Abstract

This paper presents new Arctic navigation services based on Earth Observations from Copernicus satellites. The services were developed as part of a Pre-Commercial Procurement (PCP) initiative in the MARINE-EO project. Based on end user requests, the services provide necessary information during Arctic ship navigation by detecting ships using both satellite AIS and Copernicus satellite Earth Observation imagery. Furthermore, possible icebergs are detected and distinguished from ships, and weather, wave heights and current, as well as iceberg drift are forecasted. The Arctic services also provide ship route advisory to both ship navigators and relevant maritime authorities. This route advice is based on user requests sent to the service. The digital products are delivered using different channels as a user profile in the web-based GeoPortal, through an e-mail server or FTP server. Given satellite connectivity for the ship, these services can also be provided from onboard.

1. Introduction

1.1. New Earth Observation Downstream Services

The global increase in temperature has resulted in more open waters and thinner ice in the Arctic. Waters further north than 75°N are currently accessible to commercial vessels for longer periods of the year, and in some cases the entire year. Observations from the Arctic region reveals the climate changes happen faster in the Arctic than for rest of the earth (E.g., in northern Norway, Svalbard has observed a warming of 3–5°C from 1971 to 2017), *Miljødirektoratet (2019)*. The elevated temperatures and impacts on ice are leading to maritime operations including oil and gas exploration, fishing, research and cruises. The changing marine environment results in increased navigational risks and operational challenges presented by drifting icebergs and melting ice. As the Arctic is a huge and remote area with harsh weather conditions, icebergs, unpredictable polar lows, cold climate and limited daylight during the winter, the increased maritime activities impose higher risks to mariners than other waters and complicate the execution of successful search and rescue operations and response to marine casualties. When it comes to navigation in the Arctic, there is a need to propose ship routes to save time and fuel and also to avoid the need for ice breakers. Furthermore, there is a need to have systems that can detect ice and icebergs in a reliable way and to distinguish this from ships in a reliable way. Arctic navigation also suffers from the lack of reliable nautical charts in this area.

Related to these challenges, the MARINE-EO project launched a Pre-Commercial Procurement (PCP) process to develop downstream Earth Observation (EO) Services where one of them covered detection of vessels and icebergs and route advisory in the Arctic, https://marine-eo.eu/. (MARINE-EO has received funding from the EU Horizon 2020 research and innovation programme under grant agreement No 730098.) More specifically, the Arctic service supports the users with necessary information during arctic navigation by detecting ships based on both AIS (both land based AIS and satellite based AIS) and by analyzing Copernicus satellite Earth Observation imagery, by detecting and distinguishing icebergs from ships, by forecasting iceberg drift, and by providing ship route advisory based on a list of planned waypoints and the time interval for the voyage. The main users of the services are shipping companies, ship officers, shore-based authorities in addition to other maritime stakeholders. This paper presents the main requirements and obstacles identified for these services and will briefly describe the implementations provided during the MARINE-EO PCP.

1.2. The PCP Process

MARINE-EO has been the first European Earth Observation (EO) Pre-Commercial Procurement (PCP) project which aimed to develop innovative and beyond state-of-the-art downstream applications for marine monitoring and maritime security. The MARINE-EO contractors have built on top of existing Copernicus services and other products from the Copernicus portfolio during the development of the downstream EO services. The PCP mechanism was selected since it makes it possible for public authorities and others to procure research and development of new innovative solutions before they are commercially available. It involves different suppliers competing through different phases of development. The risks and benefits are shared between the procurers and the suppliers under market conditions. In the MARINE-EO project, the PCP process started with an extensive preparation phase and was followed by three development phases. The projected ended with a demonstration and evaluation of the results.

The motivation for the PCP was to develop and provide new services using Earth Observation data from Copernicus such as satellites, ground stations and segments, contributing mission data and in-situ data coordinated by the European Environment Agency (EEA). Currently, several value-adding services exist through six different thematic areas of Copernicus services, where CMEMS is the one most relevant for the maritime domain. Even if several sets of services exist, a lot of the data is unused and not analysed or fused with other data sources, meaning that there is still a large potential to provide new and useful services. The purpose of the MARINE-EO project was to fine-tune the services to the requirements from the public procurers, but still ensuring that the resulting services have a broader set of potential users. Through this procurement, new solutions for Copernicus-based services to ensure incremental or radical innovations in the field of maritime awareness were developed and tested. In addition, supporting services to standardize usage of these services where provided, including catalogue and subscription services, service request implementation, access to Sentinel-data and other contributing missions data, and authorization and authentication services.

1.3. ArcticInfo

As one of the public procurers in the MARINE-EO project, Norwegian Coastal Administration (NCA) was the main provider of requirements to the Artic services. These services relate to ArcticInfo, https://www.barentswatch.no/arcticinfo/, which is a free service provided by the Norwegian Coastal Administration through the BarentsWatch portal, https://www.barentswatch.no/. ArcticInfo is specially aimed at fishing boats, cruise traffic and research and expedition vessels, which dominate the traffic in Arctic areas.

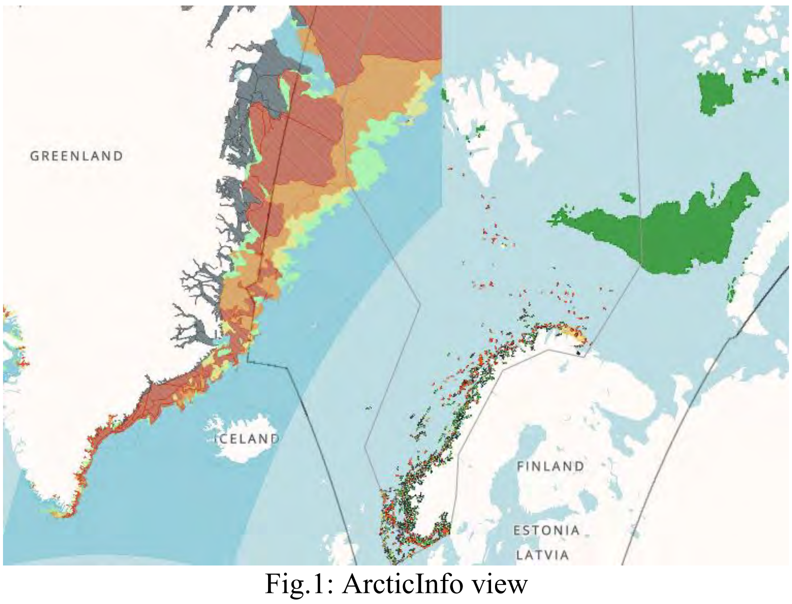

Fig.1: ArcticInfo view

The ArcticInfo service contains tailor-made information on Arctic waters based on user needs. Through this service, vessels get access to information in the Arctic from the border between Norway and The Russian Federation to Canada, including the Barents Sea and the North Sea. The service provides maps of sea ice concentration, including drift ice and solid ice weather forecasts, reporting to the Greenland authorities and AIS data that gives an overview of other vessels. With expanded access, AIS information throughout the Arctic is also available. One can also connect a user to a vessel of interest for better tracking on the map. Ship reporting are available when sailing in Greenlandic waters, Fig.1.

1.4. RouteInfo

Related to the route advice in the Arctic areas are the Digital Route service, routeinfo.no that is provided by NCA for most Norwegian ports. NCA provides these digital reference routes and route information in a geo-map platform to assist end users with route planning by searching for port, port facility, quay, or route names, https://www.kystverket.no/en/EN_Maritime-Services/Reporting-and-Information-Services/digital-route-service/. The Digital Route Service, routeinfo.no, provides quality assured sailing routes and route information for vessels arriving to and departing from ports along the Norwegian coast, all the way from the Swedish border in the southeast to Finnsnes in Northern Norway. In addition to giving access to reference routes with waypoints and legs, it also gives information about current local regulations relevant to the ports and quays, Fig.2. The reference routes can be downloaded in RTZ-format for import into any navigation platform for further route planning on board the vessels. The reference route concept has also been introduced as one of the use cases in the S-421 standard for Route Exchange. This is one of the S-100 standards maintained by IEC, http://www.cirm.org/s-421/index.html.

The digital route service allows automatic distribution of nautical information to prevent unfavourable route selections and unforeseen problems due to lack of relevant information during voyage planning. Quality assured routes and route information on board the vessels increase the navigation safety and strengthens cooperation on the bridge. The service also facilitates more efficient and time-saving voyage planning and just-in-time arrival.

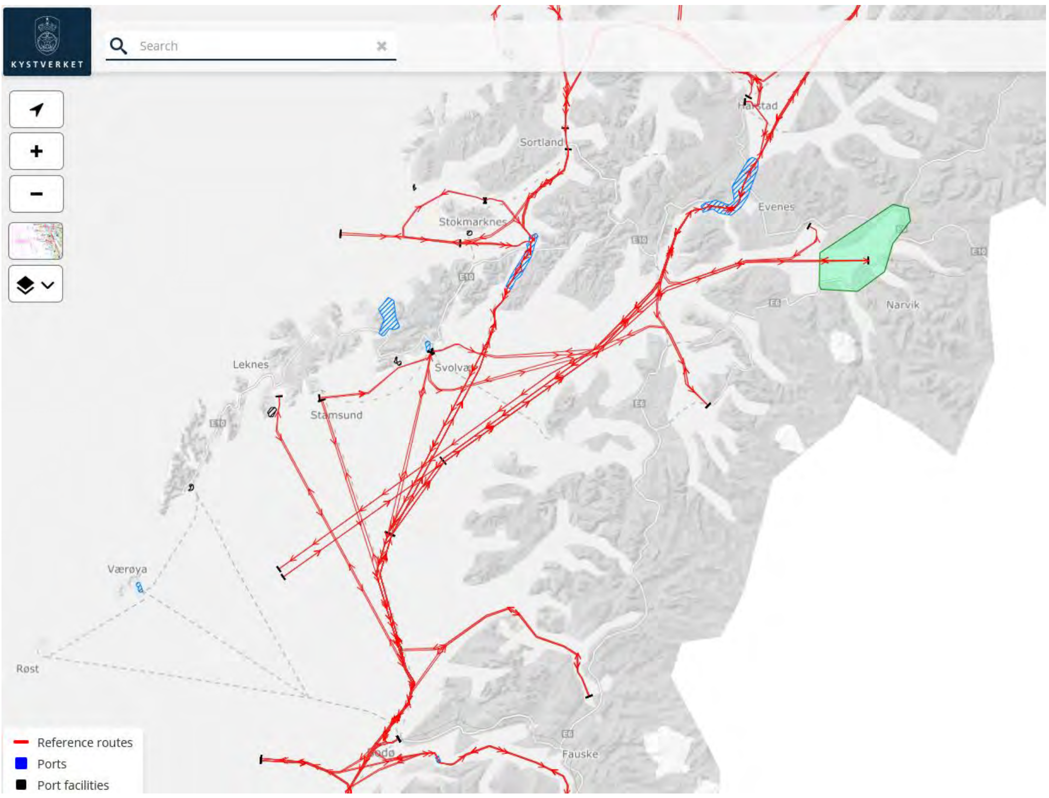

Fig. 2 Reference Routes

2. Overview of MARINE-EO Arctic Services

The Arctic navigation services cover detection and tracking of vessels and icebergs in all sizes and shapes in addition to a route advisory and iceberg alert functionality. A navigator onboard a vessel sailing in Arctic waters or operators on a VTS (Vessel Traffic Service), monitoring Arctic waters are interested in the optimum route for a voyage to avoid ice and icebergs as much as possible. The purpose of the arctic services is to provide a solution that enhances the level of trust for vessel and iceberg detection and to provide reliable information on the current ice status and forecasts that can be used both by the captain onboard and by the VTS operators. This is done by compiling satellite images and other types of critical information such as weather and wave height forecasts.

Identifying and monitoring threats of icebergs to vessels and other ocean structures is of great importance for better decision making to ensure safety, security and operational efficiency. The MARINE-EO Arctic services is based on Copernicus Sentinel-data in addition to CMEMS data and services.

One of the major issues regarding these services is the reliability of the information that detects whether an object is a vessel or an iceberg. Another issue stems from the need to share the information to vessels in Arctic remote areas due to communication and broadband coverage limitations.

In the MARINE-EO PCP, two different consortia provided two different solutions to the Arctic navigation challenge, one with focus on the route advice and the other with the focus on detection and warning of icebergs.

2.1. Ship Route Advice

One of the solutions provided detection of vessels and icebergs, iceberg drift forecast, and arctic route advisory functionalities to the user to support activity monitoring and navigation in or near the ice. These services were based on KSAT's, https://www.ksat.no/no/, infrastructure for downlinking, processing and dissemination of satellite data.

- This solution provides two types of route advisory requests: One where the vessel and iceberg detection request is based on specific area of interest given in international geospatial standard format (e.g. KML) with a related time interval, and another where the route advice request is based on the departure port/date, arrival port/date, a list of waypoints, and the IMO number of the ship.
- As a response to the route advisory request, a route is displayed with a yellow dashed line, and waypoints are displayed as red triangles. Meta data is presented on the route, Fig.3.
- Vessels and Icebergs: Vessels are shown on the map as being detected by AIS or by satellite (SAR imagery). Meta data on the vessels are shown (type of vessel, updated date/time, direction, position, size, confidence level of a detected object). Position of detected icebergs is also shown on the map in addition to meta data (type of iceberg, updated date and time, drift speed and direction, size, confidence level of a detected object).
- In this solution, meteorological forecasts (with two days simulation) regarding currents, sea ice fraction, sea surface temperature and significant wave height can be displayed on the map together with detected vessels and icebergs.
- Download: The products can be downloaded through an internet web portal with low bandwidth required.
- CMEMS products are requested for the Arctic Sea Ice concentration based on Sentinel-1B data. Vessel and iceberg detection and correlation with AIS, and iceberg drift modelling are also based on Sentinel-1B data.

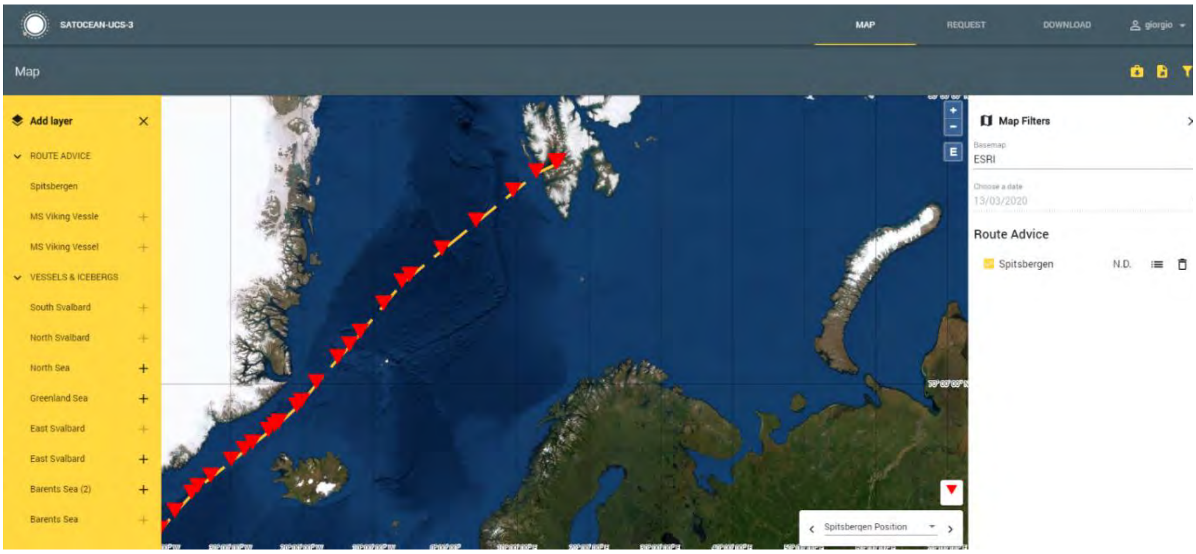

Fig.3: Route Advice

2.2. Iceberg Detection and Warning

In the other solution, satellite images from Sentinel-1 are processed to detect vessels and icebergs and to estimate the sea ice concentration. Satellite images are combined with other types of information such as AIS to increase the reliability of the detection and to improve the usability of the services for search and rescue. Also, the level of trust for vessel and iceberg detection is enhanced and more reliable information on the ice status is provided. The end user is alerted about critical situations involving vessels and sea ice (icebergs).

This solution is made up of two main components: a desktop application, which is a plugin of the QGIS open-source software, and a web-based GeoPortal, built upon the SEonSE platform by e-GEOS.

- The request is created by entering the planned route as a list of waypoints, an area of interest either drawn on a map or given as a bounding box with four LAT/LON coordinates, the actual dates and the requested services (route advisory and/or the ship/iceberg detection functionality).
- Notification: When the product is ready, a notification is sent to the user by e-mail. Then, the user can log into a portal and display the downloaded data and search for information, such as:
    - Correlation between vessels detected by AIS and by satellite imagery, information (including picture) of vessels identified by AIS and the past track of the vessel
    - Vessels detected only from satellite images, not from AIS
    - Iceberg detection: Position of iceberg and the confidence that this is an iceberg, not a vessel or anything else.
    - Iceberg drifting direction and speed estimation from satellite imagery.
    - Ice concentration estimated from satellite radar imagery.

Since internet connection is not reliable in the Arctic and the available bandwidth is limited, especially for vessels sailing further north than 75°N, the user can choose to download the product directly from an FTP repository. The downloaded data can be opened in any tool supporting the most common GIS formats.

In the daily process, the system can check whether dangerous events involving specific vessels are going to occur, such as vessels heading towards an iceberg or approaching the icepack. When such situations are predicted, an alert is triggered, Fig.4. The user receives a notification by e-mail containing all relevant details related to the event. In addition, the vessel and iceberg can be displayed on a map both in the Desktop Application and in the web-based GeoPortal.

Fig.4: Iceberg alert

3. Usage of MARINE-EO Arctic Services

3.1 Further development of MARINE-EO Arctic Services

The Marine-EO Arctic solutions can be further developed to give added value to the current system provided by the NCA to ensure full automation and seamless digitalization and information sharing between ship-ship, ship-shore and shore-shore systems. The route advice service can be seen as an extension of the reference route service provided by NCA. The MARINE-EO Arctic services manage to distinguish between ships and icebergs, and the solution also has the possibility to identify ships that have switched off the AIS. This can be a very useful contribution to improve the situational awareness for the VTS operators during their daily work. The Arctic services are well within the IMO e-navigation initiative in terms of maritime safety and efficiency. All operations regarding Arctic ship navigation, automated ship reporting, route optimization and monitoring, navigation warnings, maritime safety information, etc. play key roles to achieving maritime safety, security and efficiency. Another important aspect is to use an entrusted and reliable Maritime Connectivity Platform with great degree of interoperability and secure digital infrastructure for the maritime community to implement secure data integrity, secure transport of data, service creation, deployment and discovery. In addition to this comes the usage of the standards covered by the S-100 framework. An extension here would be to provide the route advice in the S-421 format to ensure that this can be presented on ECDIS systems following the S-100 framework. A further extension would be to standardize the names of these routes. This can be done through international bodies such as IMO, IALA, IHO, which most maritime authorities are participating in. This can then be implemented as Maritime Resource Name (MRN). Another extension regarding the Arctic services is that the ship advisory should take into account the ship's parameters, weather and current parameters, not only the iceberg detected and the ice coverage. Also, the user should get an overview of the assumptions that have been made to come up with the actual route advice.

3.2 Communication needs

Reliable and efficient communication in the Arctic area is still an issue. However, the development and launch of VDES, Fig.5, will improve both the ship-ship and ship-shore communication in remote areas. A satellite component (VDE-SAT) is being developed and tested, using the Norwegian NorSat-3 satellite. VDES (VHF Data Exchange System) is the new international standard for two-way communication at sea, https://www.iala-aism.org/content/uploads/2018/05/D1.14-Draft-IEC-Technical-Specification-for-VDES-2017.pdf, https://spacenorway.no/vhf-data-exchange-system-vdes-page-under-development/.

VHF, Very High Frequency radio (156-174 MHz) was originally devised as a system for two ways voice communication between ships and between ship and shore, including vessel traffic services, ports, locks, bridges etc. It has been used for general maritime navigation and traffic control. All ships and most small seagoing crafts have stationary or hand-held VHF equipment onboard. VHF radio has a typical range of 40-100 nm, depending on the height of the sending and receiving antennas.

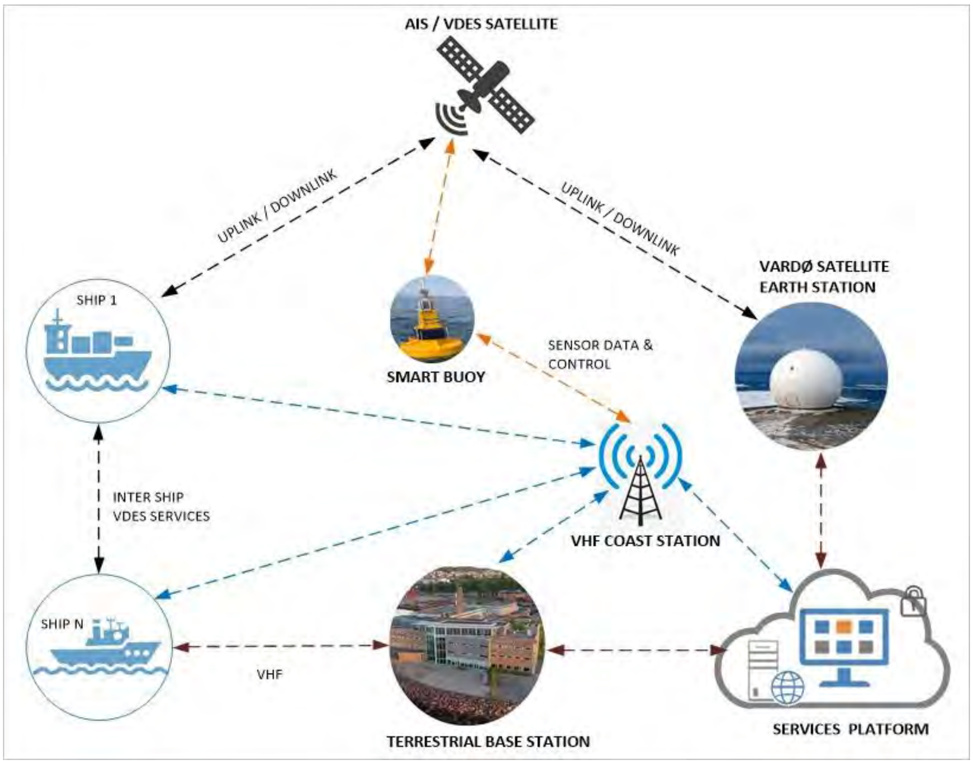

Fig.5: VDES – VHF Data Exchange System [Source: NCA]

In later years, some of the VHF frequencies are also used for data exchange with low bit rate through the AIS system, including the use of certain application specific messages (ASM). There are currently two AIS channels for terrestrial use and two for satellite use. These services will now be extended into the VHF Data Exchange System (VDES), including AIS as well as new higher capacity data channels.

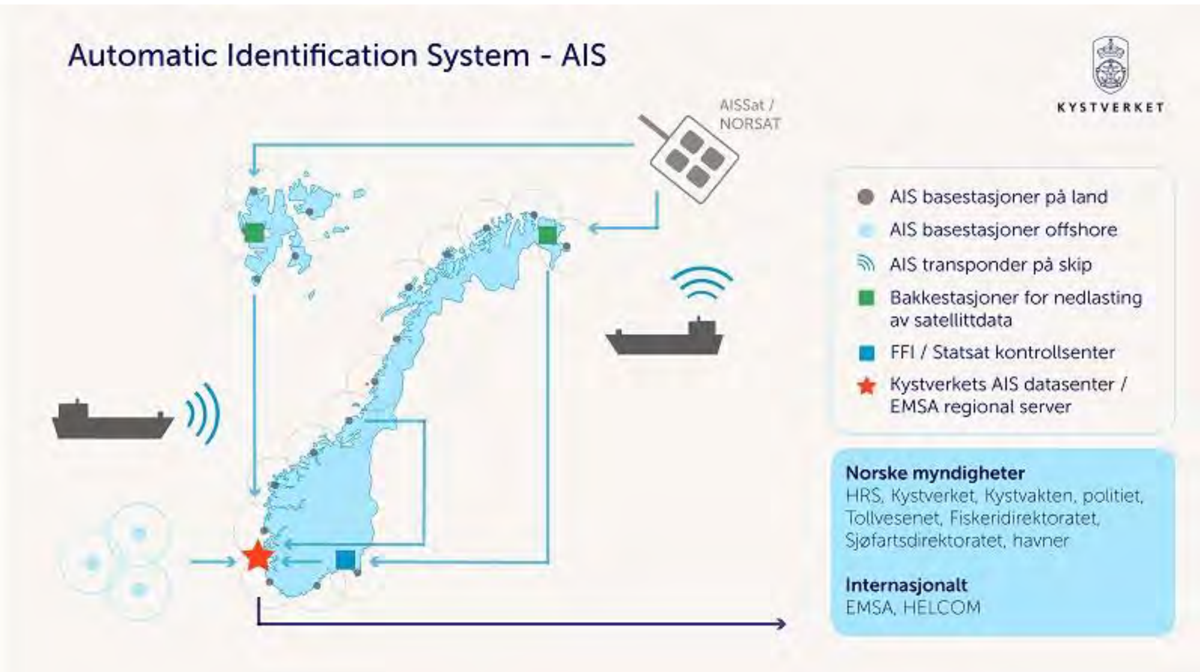

Fig.6: AIS Satellites [Source: NCA]

The new Norwegian satellite NorSat-3 is more advanced than its predecessors because in addition to the AIS receiver, it is equipped with an experimental navigation radar detector (NRD), which can detect radar signals from ships, Fig.6. The NRD is primarily a technology demonstrator focusing on gathering more data from the Arctic region, but it will also contribute to a more comprehensive maritime traffic picture. The new payload will find ships by capturing and locating signals from civilian navigation radars. Thus, the Norwegian Coastal Administration (NCA) will be able to verify the AIS information and also be able to detect ships that are not emitting AIS signals.

3.3 Possible Extensions to MARINE-EO Services

Possible extensions to the Arctic services as developed in the MARINE-EO project include the following:

- Extend the route advisory function to fit to the ECDIS format to be able to present the proposed route directly in the ECDIS. The best way to do this is to follow the S-421 standard on Route Exchange that is part of the S-100 framework that the next version of ECDIS will follow.
- Add video animation of the ice using Sentinel-2 data and combine this with the already developed Arctic services.
- Integrate the iceberg alert functionality that notify a ship about a close iceberg with the route advisory functionality using formats from the international S-100 framework of standards.
- Integrate more advanced geospatial vector products similar to what can be found in www.KystInfo.no from NCA as the charts provided in the MARINE-EO products are basic compared to what is found in other products.
- The results from the MARINE-EO Arctic service can be further developed and be integrated into the Arctic information portal called of Barentswatch, https://www.barentswatch.no/arcticinfo/, to provide it in the same platform as other Arctic services.
- The process to request data from the MARINE-EO platform could have been simplified for the Arctic services to be able to receive the route advice information more automatically and with a shorter time delay.
- The alerting system for iceberg detection and changes to the route advisory can be further improved to make it more user friendly. This would be part of the next step in developing the MARINE-EO Arctic services to be fully operational, based on the operational prototype implementation that was delivered at the end of the PCP process.
- Both route advice and iceberg alerts could be sent automatically to the ship system / Navstation or to VTS monitoring systems.
- Integration of more accurate shoreline datasets covering the Arctic area in order to reduce false alarms caused by small islands and rocks.
- In case where a non-cooperative ship has been detected using satellite SAR images, it is important to get information on when and where the AIS stopped sending the AIS signal, as well as when and where the signal did resume.
- With VDES technology, it will be feasible for ships to cooperate securely by exchanging their navigational planned route or any other relevant safety information. This requires use of the international standard format such as the S-100 framework, especially S-421 on route exchange.

4. Conclusion

During the MARINE-EO PCP project, two versions of end-user-oriented services dedicated to navigational safety and efficiency in the Arctic were developed. The services were developed by consortia of private companies, under the supervision of several experts in the field. The services leverage Copernicus Earth Observation data by responding to specific operational scenarios serving the needs of the end-users, and overcoming obstacles related to storing, searching, acquiring, and processing of data. An intensive test campaign was conducted, involving end-users from various public authorities and research institutes with various backgrounds. The developed concept proved to be very useful to those that were testing the system. After this successful proof of concept achievement and comprehensive feedback provided, final developments should be planned in order to bring the solution to the market.

Acknowledgements

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Ship Design Performance and Cost Optimization with Machine Learning

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Abstract

This contribution shows how, in the preliminary design stage, naval architects can make more informed decisions by using machine learning. In this ship design phase, little information is available, and decisions need to be made in a limited amount of time. However, it is in the preliminary design phase where the most influential decisions are made regarding the global dimensions, the machinery, and therefore the performance and costs. In this paper it is shown that a machine learning algorithm trained with data from reference vessels are more accurate when estimating key performance indicators compared to existing empirical design formulas. Finally, the combination of the trained models with optimization algorithms shows to be a powerful tool for finding Pareto-optimal designs from which the naval architect can learn.

1. Introduction

Ship design typically consists of three phases, the preliminary design stage, the contract design stage, and the detailed design stage. According to *Taggart (1980)*, early design stages occupy the smallest amount of time. In the first design phases, the operational requirements are translated into technical characteristics, *Kossiakoff et al. (2003)*. This is done by finding the balance between the need of the customer and the available budged, resulting in one or more possible design solutions, *Duchateau* (*2016)*. Despite the limited amount of time spent in the early design stages, it is estimated that 60 to 80 percent of the total life cycle cost is already locked-in after the preliminary design stage, *Rehn* (*2018)*. Depending on the experience of the involved Naval Architects, this can be quite risky. The design decisions are typically hard to reverse and are also often made with limited design problem knowledge. This has been visualized per design stage in Fig.1 by *Duchateau, (2016)*. The figure shows the consecutive design stages, the committed costs, problem knowledge and design freedom.

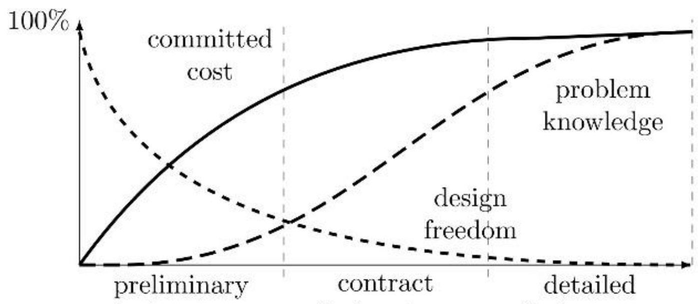

Fig.1: Generic design timeline by *Duchateau* (*2016)*

In this paper a solution is presented on how, in the preliminary design stage, more knowledge can be used when making decisions. With the method described in this paper, naval architects are better supported by data to make design decisions instead of relying only on instincts, knowledge and experience. The decision support is in the form of machine learning models which can be used to validate ideas, assumptions, and design variations. This helps the naval architect in avoiding innovation risks and to find better design variations. On top of this, without much additional effort, the naval architect can use the trained machine learning models in combination with an optimization algorithm. This optimization algorithm can then be deployed for searching advantageous and competitive design variations. The only requirement for the so-called reference optimizer to work properly is enough relevant ship data, and a properly setup design problem.

2. Background and Related Work

In ship design, two design philosophies can be distinguished, the empirical and the simulated design method. The empirical design method is based on reference data of similar built vessels. The simulated design method uses estimations, calculations and simulations to optimize the economical and physical characteristics of the to be designed vessel.

2.1. Empirical Design Method

In the Empirical Design method, the main dimensions are based on similar built vessels. Similar vessels are marginally improved or the data from similar vessels is used to make a regression model, after which empirical design formulas can be deducted. Examples of empirical design equations have been created by *Watson (1998)*, *Schneekluth and Bertram (1998)*, *D'Almeida (2009)*, *Andrews (1998*), *Molland (2011)* and *Papanikolaou (2019)*. With these equations a naval architect can easily estimate ship design parameters. The equations are usually calibrated for different ship types. As empirical relations are based on knowledge from previous work, it is important to handle the relations carefully. It is the naval architect's job to update the relationships whenever possible *Molland (2011*). However, in reality updating is often not regularly done, and the equations are only available for the most popular ship types. A second note to keep in mind is that extrapolation of the regression models remains problematic *Papanikolaou (2019)*.

2.2. Simulated Design Method

If no or very little data of similar ships is available, it is not possible to use the Empirical Design Method. The naval architect is in this case is forced to design a ship from scratch using estimations, calculations and simulations. An efficient way to do this is by utilizing a parametric 3-D model and connect it to simulation software. General design knowledge and design experience is used to setup this 3-D parametric model. Examples of the parametric modelling approach can be found in e.g. *Marzi et al. (2018)*, *Priftis et al. (2016)*, *de Winter et al. (2021)*. Typically, after a parametric model is setup, the designs are optimized for their economical and physical characteristics with optimization algorithms *de Winter et al. (2019)*.

A second, more automated, parametric design method has recently been proposed by *Charisi et al., (2019)*. In this work it is shown that knowledge-based engineering is a good option when designing a ship when not enough similar ship data is available. With knowledge-based engineering, general multidisciplinary knowledge is translated in individual product models / building blocks which represent a small part of a vessel. These product models are then used, scaled, and combined into an entire ship design in an object-oriented way.

3. Data Description for Reference Studies

The solution proposed in this paper utilizes both the power of empirical and parametric optimization. To get up to date empirical formulas, data is needed. In the past decades, a lot of data services have become available for the maritime industry. The most prominent ones are:

1. World Fleet Register, a ship data and intelligence platform from Clarksons Research with data about ship earnings, vessel parameters, and new-build data.
2. IHS Markit, in the maritime portal of IHS Markit reports static ship data of existing and scrapped ships.
3. BRL shipping consultants, in the subscribers' area of BRL static data and reports are available about new build vessels.
4. Marine Traffic, even without logging in it is possible to obtain the location of vessels plus general static ship data.

All this static and operational data has been collected and aggregated into more than 100 particular data fields per vessel. Examples of collected data fields are: Length, breadth, draft, block coefficient, light ship weight, dead-weight, maximum continuous rating of the engine, maximum speed, but also more ship specific data fields for specific ship types such as: Bollard pull, passenger capacity of urban transportation vessels, number of car lanes, crane capacity, hopper volume of dredgers, and ice class qualification.

This data can be used in a reference study in the preliminary ship design process since design trends can be visualized, design trends can be learned, and gaps and competitive advantages in the market can be found.

3.1. Visualizations

After the relevant parameters for a vessel type have been selected, the parameters can be summarized and plotted. When three parameters are relevant it is still possible to visualize it in two dimensions as can be seen in Fig.2.

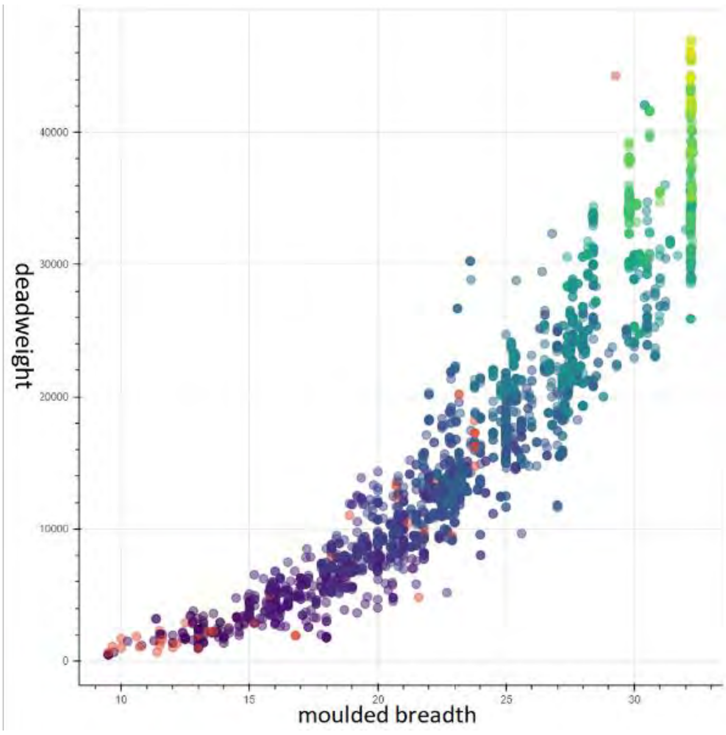

Fig.2: Container vessels color-coded by TEU capacity

However, it is often the case that more than three parameters are relevant in the preliminary ship design stage, which makes it challenging to visualize. To still be able to investigate a selection of ships or design variations with more than three parameters simultaneously, parallel coordinate plots can be used *Heinrich and Weiskopf (2013)*. As an example, a parallel coordinate plot, Fig.3, was made for several hundred container vessels with the length between perpendiculars of 175 m and 200 m. Every line in a parallel coordinate plot represents one vessel, every axis in the *y* dimension represents a range of values belonging to one design characteristic.

As can be visually inspected from Fig.2, the moulded breadth has a maximum on 32.4 m, the well-known maximum width for ships to still be able to sail through the Panama Canal. This maximum moulded breadth can also be seen in Fig.3. Moreover, it is now also possible to simultaneously see all other relevant parameters of the container vessels. For example, the limited draught for the majority of vessels in this selection is smaller than or equal to 12 meters, also an important Panama Canal dimension. Besides this, you can simultaneously see the conflicting relationship between block coefficient (Cb), and maximum continuous rating (MCR) and their influence on service speed. The vessels with a high block coefficient, small maximum continuous rating, also have a slow service speed and vise-versa. When designing new vessels, these plots can be very helpful for the naval architect.

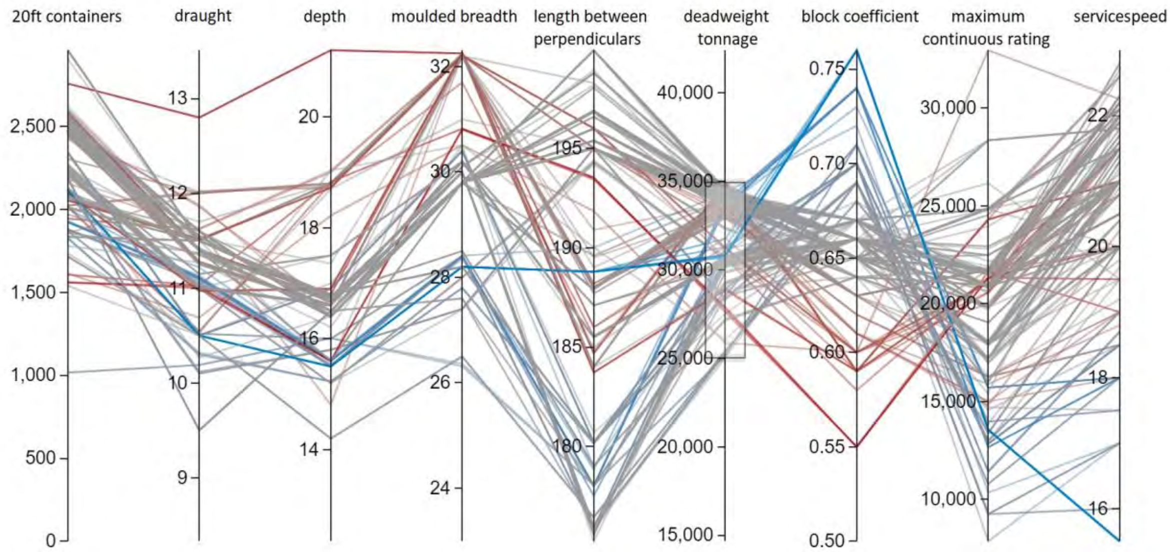

Fig.3: Parallel coordinate plot of container vessels color-coded by block coefficient, and a deadweight tonnage selection between 25000 and 35000 t

3.2. Data Pre-processing

The preliminary data analysis showed duplicate vessels and vessels which are very similar. To make sure that specific vessels are not over-represented, data pre-processing has to be done. The pre-processing consists of three steps. First all but one of the vessels with exact duplicates are deleted. Ships are considered to be duplicates if their gross tonnage, length between perpendiculars (Lbp), breadth overall (Boa), draught (T), and MCR are equal. Then all but one vessel out of a series of sister vessels are deleted. If the earlier mentioned variables are all within 1 percent of each other, the vessels are marked as too similar.

Reasons for deletion of duplicates and very similar vessels are to prevent the potential over-fitting of machine learning models. If a series of sister vessels would be present, the machine learning model would automatically put more weight on the sister vessels compared to one unique vessel. A second argument to delete sister vessels is, once a machine learning model has learned from a vessel, a second sister vessel does not add much knowledge but will only add computation and training time.

The third pre-processing step consists of creating second degree polynomial and interacting features. This is done to generate more potentially interesting features from the ship design parameters that are known. The two degree polynomials and interacting features of the example $[a,b]$ would be: $[a,b,ab,a^2,b^2]$. This way, the machine learning models have more features to learn from which leads to more accurate results.

4. Methodology

This section describes how the empirical design method is used in combination with an optimization algorithm in the so-called reference optimizer. As mentioned in the related work section, it is often the case that the empirical design equations are not available for a specific ship type or that the available equations are outdated. This is unfortunate since designing ships with wrong or outdated design equations will lead to sub-optimal designs. The empirical design equations are therefore replaced with machine learning models. These machine learning models make sure that it is no longer need to solely depend on predefined equations or the experience and knowledge of naval architects.

Machine learning models are used to learn the relationships, similarities, and trends between hundreds of vessels. However, for machine learning models to work properly, the relationship between the dependent and independent variables need to be learned. The dependent and independent variables are chosen by the naval architect. The machine learning models learn the relation between the independent and dependent variables in the training phase. After the training phase, the trained machine leaning models are coupled to an optimization algorithm which can exploit the trends learned and search for optimal design configurations which outperform the existing designs.

4.1. Setup Design Challenge

For the machine learning algorithm to work well a design challenge should be setup by the user. The design challenge consists of three parts, the design variables/parameters, the constraints/limitations, and finally the objectives.

Design Variables

The variables are setup by choosing the design parameters which have a significant influence on the final design, and which are allowed to vary. The allowed variation in the variables are controlled with a user defined lower and upper limit. However, the limit cannot be smaller or larger than the smallest and largest ship in the collection. Example of a set of design variables are: *Length between perpendiculars (Lbp), draft, draught (T), Breadth overall (Boa), block coefficient(Cb)*, and *service speed (V)*.

Constraints

The design constraints are also set by the user, design constraints are typically hard limitations or strong wishes for the to be designed ship. Examples of constraints are: capacity of 30,000 tons, a cargo capacity of 2000 twenty-foot equivalent container units, a *length overall* (Loa) smaller than 180 m, and a *draught* (T) of not more than 12 m.

Objectives

Typical objectives of a ship design are the key performance indicators (KPIs) which deal with operational expenses or initial investments. Ideally, they are as low as possible however they most often do not go hand in hand and are most of the time conflicting. Examples of two objectives are: minimize the *light ship weight (LSW)* while maximizing the *dead weight (DWT)* capacity, while minimizing the *Maximum Continuous Rating (MCR)* of the main engines.

Once the design variables, constraints, and objectives have been set by the user. The relationship between the variables and the constraints and objectives can be learned.

4.2. Random Forest Regression

A random forest regression model, *Breiman (2001),* learns the relationship between the features and one target variable. In our case the features are the design variables plus the polynomial features and the target variable one of the constraints or one of the objectives. Therefore, for each constraint, and for each objective a new unique random forest regression model is trained.

The random forest regression model learns the relation between the features and the target by fitting a multitude of decision trees. One decision tree is fitted to learn the relation between a set of random selected features with the corresponding target values. The data with the random selected features is sequentially greedily split into two sub-samples based on one of the features, until the number of samples in the nodes reach a threshold value. Resulting in an upside-down tree with nodes, branches for splits, and leaves with similar target scores.

Once e.g. 100 decision trees have been trained with the 100 randomly selected feature sets, the random forest is done training. The trees in the forest can be traversed which makes a prediction of the target variable for an unseen combination of feature values possible for each tree. These 100 outcomes of the 100 decision trees are then averaged into a final prediction. This process has been visualized in Fig.4. Because a multitude of trees are fitted, the random forest regression model is robust against outliers in the training data. However, due to the fact that the final score depends on the average of all the trained trees, the random forest regression model is not capable of extrapolation.

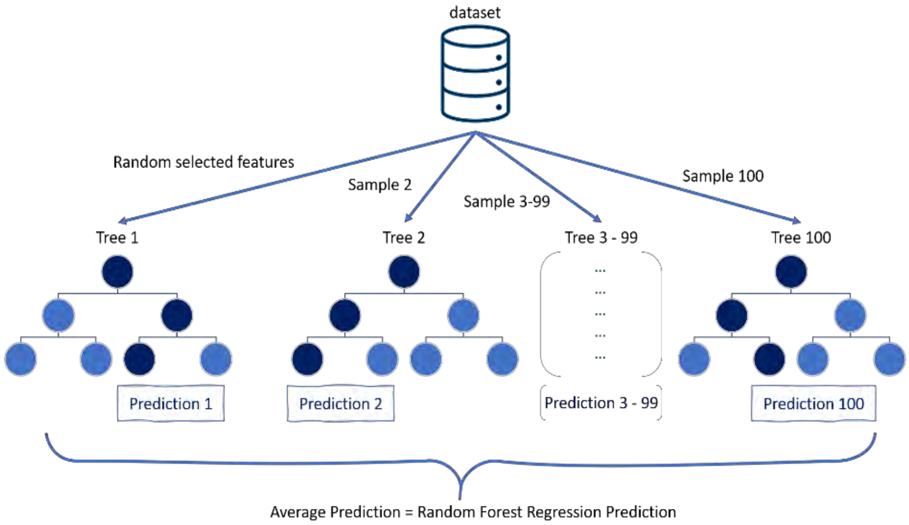

Fig.4: Random Forest Regression Model

4.3. Isolation Forest

Not only the user defined constraints limit the search space. The search space is also limited by an anomaly detection algorithm. The anomaly detection algorithm used is named Isolation Forest *Liu et al. (2008)*. Isolation forest is an unsupervised machine learning algorithm which test how easy it is to isolate certain data points. It does this by recursively splitting the data by randomly selecting a variable and a random split value between the lower and upper limit. If a sample is easy to isolate by randomly splitting the data set, it is marked as an anomaly. A sample that is hard to isolate versus a sample that is easy to isolate is visualized in Fig.5.

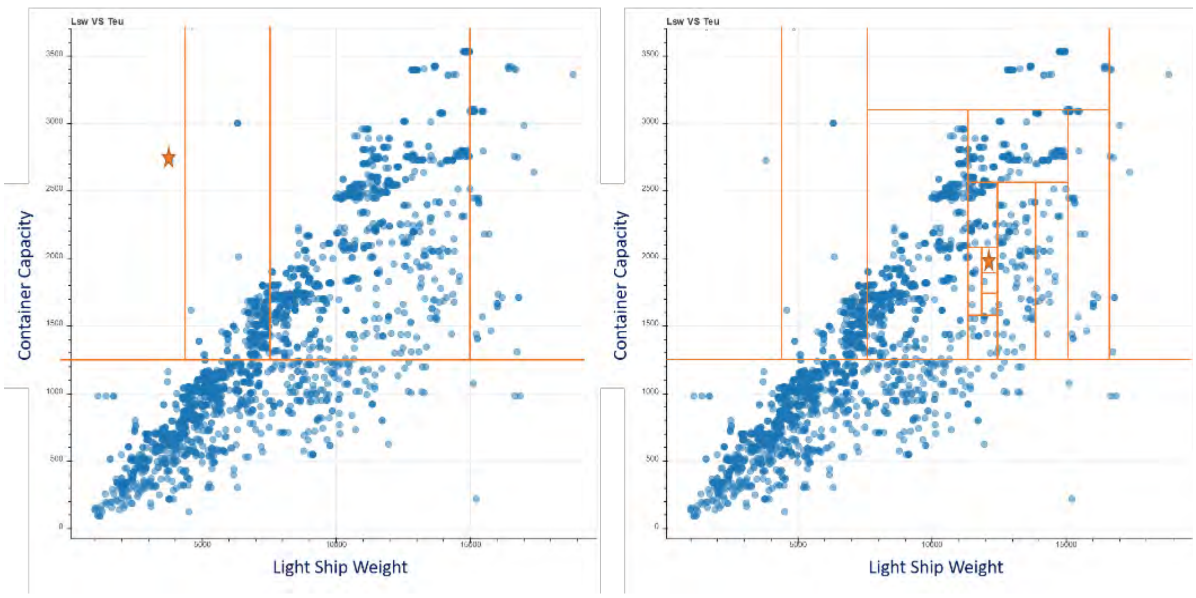

Fig.5. Isolation forest with easy to isolate sample and hard to isolate sample

In practice, this means that in case a design variation is very unique and lies outside of the trend, or if the database contains a ship with length by accident reported in feet instead of meters, it is marked as an anomaly. When searching for a new design variation, design variations which are marked as anomalies by the isolation forest will no longer be considered. This is the case because they do not follow the pattern and therefore their prediction is probably incorrect. On top of this, the isolation forest will make sure that the design variations will not exceed the limits, so that the random forest regression model is not forced to extrapolate.

4.4. Optimization Algorithm NSGA-II

The reference optimizer, searches for optimal design configurations which do not violate any of the constraints. This is done with a multi-objective optimization algorithm named Non-dominated Sorting Genetic Algorithm II (NSGAII) *Deb et al. (2002)*. NSGA-II is coupled with the design challenge by connecting the design variables, constraint and objective random forest models. First, NSGA-II is allowed to vary the design variables between the user defined lower and the upper limit, then for each try a design variation is tested. The evaluation of each design variation is done by using the random forest regression models to predict the constraint and objective scores. The objective and constraint scores are then combined with the design variable values and tested to see if the combination can be easily isolated by the Isolation Forest. Once the isolation score, the objective score, the constraint score is evaluated it is given back to the NSGA-II algorithm. The NSGA-II algorithm includes the evaluated design variations in the population of previously evaluated solutions and then new solutions are generated with the non-dominated genetic sorting strategy. NSGA-II is allowed to try 4000 design variations. After which the optimal designs are reported, and visualized on a Pareto frontier.

5. Experiments

To validate the models and the algorithms, different experiments are conducted. The first experiment is setup to test the predictive capabilities of the random forest regression models. In the second experiment a set of ships is intentionally modified to see if the isolation forest is capable of identifying the newly created anomalies. Finally, in the last experiment, we connect everything and generated design variations for a novel container ship. For the experiments 2538 container ships are used. 1219 of these vessels have the duplicate characteristics as described in Section 3.2 and are therefore not further used

5.1. Experiment 1: Random Forest Regression Test

The random forest regression models are intended to predict the performance and cost of ship designs of the future. In this experiment this situation is mimicked. Three different KPIs are learned by the random forest regression models with data from 1019 ships build before 2005, then the random forest regression models are tested with data from 96 ships build after 2010. By comparing the predicted values with the actual values it can be determined if the trained random forest regression model is good for use in practice.

The KPIs that are predicted in this experiment are LSW, MCR, and DWT. The KPIs are estimated with the random forest regressor and with empirical design equations for the specific KPIs. The design variables used to predict LSW are [*Lbp, Boa, T, Cb, MCR*]. The design variables used for MCR are [*Lbp, Boa, T, Cb, V*]. The design variables used to predict DWT are [*Lbp, Boa, T, Cb*].

5.1.1. Random Forest Regression Results

The accuracy of the random forest regression model is determined with the R^2 measure *Miles (2014).* This measure compares the real KPI values with the predicted values and see how much variation of the dependent variable can be explained by the model. With R^2 scores of 0.93, 0.90, and 0.95 for LSW, MCR, and DWT, it can be confirmed that the random forest regressor is capable of capturing a lot of the variance.

5.1.2. Empirical Design Equation Results

For Light Ship Weight for container vessels the Empirical Design Equation of *D'Almeida (2009)* is used. The equation for light ship weight is dependent on the *steel weight (SW)*, *outfitting & equipment weight (OEW)*, and *machinery weight (MW)*:

$$LSW = SW + OEW + MW$$
$$SW = 0.0293 \cdot \mathrm{Lbp}^{0.0293} \cdot \mathrm{Boa}^{0.712} \cdot \mathrm{T}^{0.374}$$
$$OEW = 0.1156 \cdot (Lbp \cdot Boa \cdot)^{0.85}$$
$$MW = 2.35 \cdot (MCR/0.745699872)^{0.60}$$

As you can see the same independent variables are used here as in the random forest regressor model. However, the estimate of this empirical formulation only obtains an R^2 score of 0.84.

MCR can be estimated with the empirical formula based on the Admiralty Constant formula from *Schneekluth and Bertram (1998).*

$$MCR = \frac{\Delta^{2/3} \cdot V^3}{C}$$

Here, Δ is displacement. The Admiralty constant itself (*C*) is estimated with the reference vessels from before 2005. The mean of all the Admiralty constants C that followed from the vessels before 2005 is used to make predictions for the container vessels after 2010. The R^2 score for this formula is 0.87, again a worse R^2 score compared to the random forest regressor.

The empirical formula for DWT is:

$$DWT\ = \Delta - LSW$$

Since the empirical equation for light ship weight has a worse R^2 score compared to the random forest regressor, it is no surprise that also for DWT, the R^2 score of 0.89 is lower compared to the R^2 score of the random forest regressor.

5.2. Experiment 2: Isolation Forest Test

In the isolation forest experiments, the isolation forest is trained with the data from the container vessels as described earlier. After this, two data fields per vessel are modified to create impossible design parameter/KPI combinations. All vessels are then evaluated by the trained isolation forest to see if they are marked as an anomaly or not. The modified design parameters/KPI values and the percentage of anomalies detected are presented in Table I.

As you can see, the extremer the vessels are modified, the more vessels are marked as anomalies by the isolation forest. From the results it can also be seen that there is a small percentage of vessels that have been radically changed, but have not been marked as an anomaly, this indicates that the anomaly detection algorithm does not cover all anomalies and that the naval architect should pay attention when analysing the results and do a few integrity check on the results.

Table I: Modified columns and classified anomaly percentage after this modification.

Modified Columns	**Anomaly Percentage**
no modification	15%
Lbp/1.1, *T* × 1.1	36%
Lbp/1.25, *T* × 1.25	56%
Lbp/1.5, *T* × 1.5	88%
Lbp/1.75, *T* × 1.75	99%
Lbp/2, *T* × 2	100%
MCR/2, *V* × 2	95%
LSW/2, *Cb* × 2	97%
Lbp/2, *DWT* × 2	97%
Cb/2, *Lbp* × 2	100%
T/2, *Cb* × 2	100%
Cb/2, *V* × 2	100%

5.3. Experiment 3: NSGA-II Test

For this experiment it is assumed that the random forest regression model and the isolation forest perform as intended so that the NSGA-II algorithm can be tested. If the NSGA-II algorithm can find feasible and realistic Pareto-optimal solutions, we can confirm that the reference optimizer works as intended.

The reference optimizer is tested on a container ship case. In this case NSGAII was allowed to vary the main particulars of the vessel as described in the experiments before. The LSW and MCR are minimized, while the DWT capacity should be larger than or equal to approximately 28000 tonnes. The results are visualized on the Pareto frontier in Fig.6.

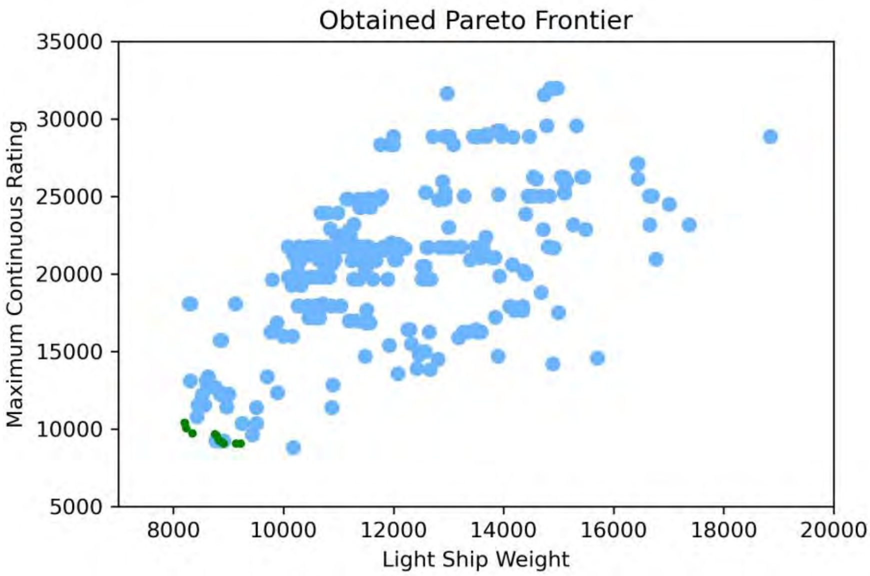

Fig.6: Obtained Pareto efficient solutions for test case. Blue indicates existing vessels which does not violate any of the constraints while green indicate the proposed solutions.

NSGA-II was capable of finding 14 Pareto efficient solutions along the Pareto front intermitted by Pareto efficient existing vessels. As previously described the algorithm only uses data and does not know any physics, it is the task of the naval architect to double check the feasibility of the proposed solutions. In this case, the physical integrity of the proposed solutions are checked with the DWT formula.

The weight balance of the vessel i.e. the sum of the DWT and LSW need to be in line with the corresponding main dimensions ($Lbp \cdot Boa \cdot T \cdot Cb \cdot \rho$). In this case, the found maximum deviation for the existing vessels is 7% with an average of 0.2%. The deviation for the proposed vessels is at the highest 2.6% off with an average of 1.8%.

In the parallel coordinate plot in Fig.7, the main dimensions and the resulting performance indicators on weight and installed power of the proposed solutions can be evaluated and compared with the existing vessels.

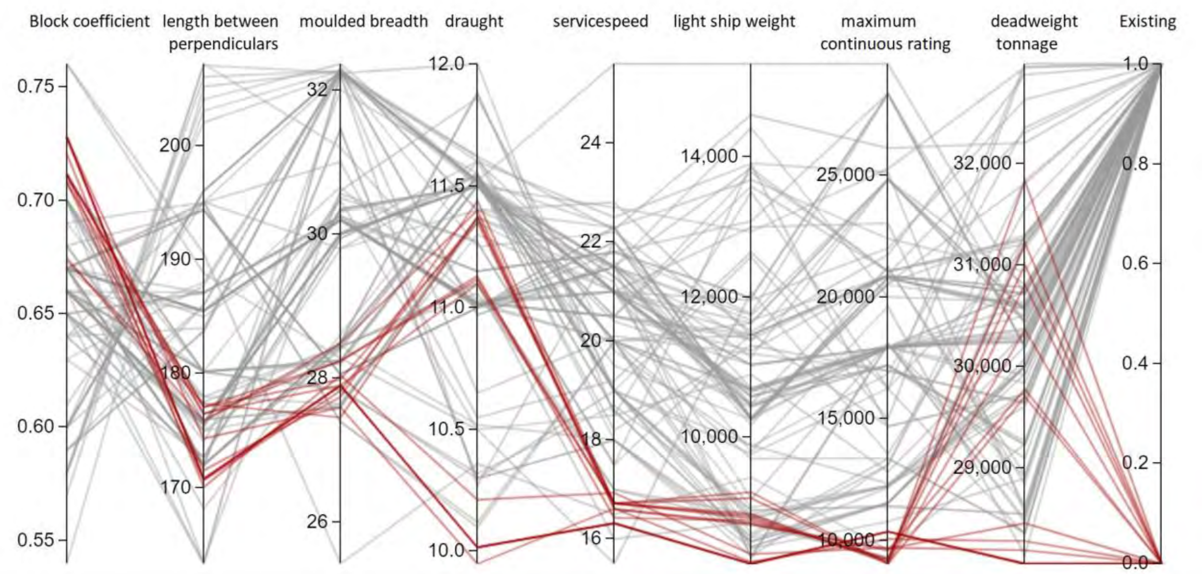

Fig.7: Parallel coordinate plot of the proposed solutions in red versus the existing vessels in grey.

6. Discussion

The reference optimizer has two drawbacks. The first drawback of the reference optimizer is that it need a sufficient amount of good data for the random forest regressors to make accurate predictions. Good data without mistakes is important since otherwise the random forest regressors will learn a wrong trend and the predictions will be off.

A second drawback of the reference optimizer is that the design challenge should be set up properly. For this, the naval architect might need to learn a few things about training machine learning algorithms. During the training at least the choice of what to choose for independent and dependent variable should be addressed in combination with different performance metrics.

7. Conclusion and Future Work

In this paper an alternative generic way is presented on how naval architects can make preliminary design decisions by using visualization techniques and machine learning algorithms.

The experiments in this paper show that random forest regressors can give better estimations for light ship weight, dead weight, and maximum continuous rating compared to empirical design equations often used by naval architects. Besides a better estimation of key performance indicators, the random forest regressors are also capable of predicting key performance indicators for which no empirical design equations are readily available in literature.

After training the random forest regressor and an anomaly detection algorithm, the models are coupled to a multi-objective optimization algorithm. This setup is capable to automatically generate optimal design configurations for preliminary ship design problems. As a practical use case, a container vessel design challenge has been solved. The setup proposed 14 new Pareto-efficient solutions. The preliminary designs consisted of main particulars of the vessels plus the key performance indicators like light ship weight, maximum continuous rating, and deadweight. After this, the preliminary designs have been evaluated with integrity checks to validate the designs.

For future work it is intended to improve the performance of the machine learning models even further and integrate a more robust anomaly detection algorithm to detect obvious mistakes better.

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SHIP - Ship Holistic Integration Platform

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Abstract

SHIP is a tool designed to handle the shipbuilding process in one single digital platform. The application, natively programmed for portable devices, makes possible to exploit the modern connectivity technology to unify communications, to facilitate access to documents, speed up workflow and increase the geographical and temporal availability of information. SHIP objective is to increase collaboration among stakeholders, to obtain a concurrent engineering implementation and to gather knowledge along the process. SHIP aims to supply Key Performance Indicators (KPIs) to better control the shipbuilding process. This paper describes the use of Object-Oriented Programming to create the tool and the implementation of persistent storage to continuously expose data and to keep the process constantly updated.

1. Introduction

Shipbuilding consists of different phases, a path, that often overlap in their development, in each phase we find different actors, sometimes interacting with each other. These actors can be internal to the shipyard or external suppliers. Each involved party uses different tools or tool of the same kind with little synchronization of input/output data. The shipyard learns only partially during the path; that is, the knowledge created during the path remains partly as a company acquisition and asset; mostly resides in the actor who produced it and it will not, in general, contribute effectively in the future.

This path is nothing else than the ship construction process, a process understood at the same time technical and managerial. To be effective, the process needs coordination and that the knowledge learnt is reused. On the contrary, the result will not be technically compliant with the initial request and/or not compliant with the results expected by the shipyard. Thus, different scenarios can occur; a ship, for instance, fit for sea but without achieving the intended operating result for the shipyard.

The use of a single tool would be of great advantage. The shipyards would have greater control, the managers would be able to check technical and management performance indicators (KPIs) and react promptly to deviations. Such a tool must consider the ship as a whole and integrate the process from the very beginning to resolve conflicts, manage collaboration and increase process knowledge; knowledge that will be reused in future projects.

The paper starts from a quick summary about design methodologies, follows with a proposal of a holistic tool natively designed for portable devices as a means to provide a single tool to shipyards to get the control over the process and to be informed anywhere and at any time.

2. Ship design methodologies

The common adopted procedure for the ship design is the well-known *design spiral* first introduced by *Evans (1959).* The design spiral shows the iterative nature of ship design. According to Evans, ship design is a sequential and iterative path divided in several disciplines. During time, many authors have actualized the Evans scheme; *Andrews (1981)* introduces time as a third dimension and he represents the design process as a “corkscrew”.

Mistree et al. (1990) adds the concept of concurrent engineering to Evans’s model; introducing “*The Frustum of a cone”* which shows that tasks can depart towards different direction and that the design process is not a sequential process. By figure 1 he shows that, as a design process progress and decisions are made, the freedom to make changes is reduced while the knowledge about the product increases.

Nowacki (2016) describes a design strategy where concurrent engineering is the core concept. Tasks can be realized in any order; the designer is free to jump from one task to another; in case any information is missing he can make hypothesis or approximation. This way of proceeding reduces the time necessary to complete the project and the ship will be delivered in less time. Nevertheless, the parallel way of work introduces the necessity of the mutual dependencies control, coordination and a good team work. Designer have to supply information to the organization in such a way the enterprise can manage the uncertainty and it can change the strategy with agility.

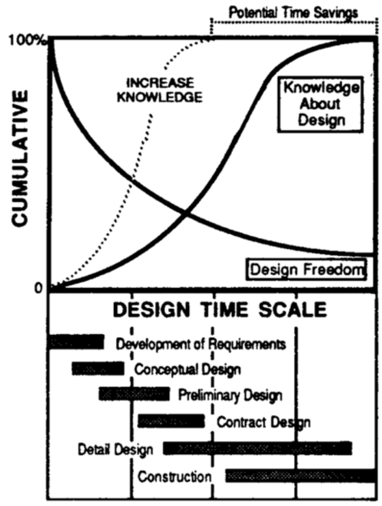


Fig.1: *Mistree (1990)* Increasing the amount of knowledge about a product at an early stage

3. The proposed tool

As seen in the introduction a single tool able to control the different stages and to keep shipyards informed about the process is for shipyard convenience. In the following, I will describe how a holistic approach and concurrent engineering can be synthesized in one single tool which will be able to gather knowledge and improve coordination.

3.1 The ship as a whole

A ship is a complex product with a multitude of interaction among different disciplines, different actors (technicians, engineers, salesmen/women, purchasers, ….) and different services (Procurement, Production, Operation, …).

Recalling Fig.1, the early stage is the favored place where to inject the knowledge in order to gain in the succeeding ones; also, the conceptual design stage is fundamental, here the majority part of the project cost is defined, *Dierolf and Richter (1989*) and *Calkins et al. (2001)*. All decisions taken later and which are not outside of the initial scope have less influence on the total cost and performances.

We shall be able to collect, acquire as much information as possible from the experience to gain understanding of the process. The information will be, then, used profitably in the early stages to take advantage later in terms of time and costs savings. In other words, one could say that the area below the 'Knowledge About Design' in Figs.1 and 2 is the available knowledge for the product.

From the Oxford English Dictionary, "knowledge: facts, information, and skills acquired through experience or education; the theoretical or practical understanding of a subject". The more information we will be able to collect the more knowledge we will have available.

We need to acquire facts and information from the shipbuilding process and to do so we need to address the ship as a whole. The mental map in Fig.3, in a simplified representation, shows, as a bird's eye view, the interactions among different equipment and different disciplines or services which constitute the vessel.

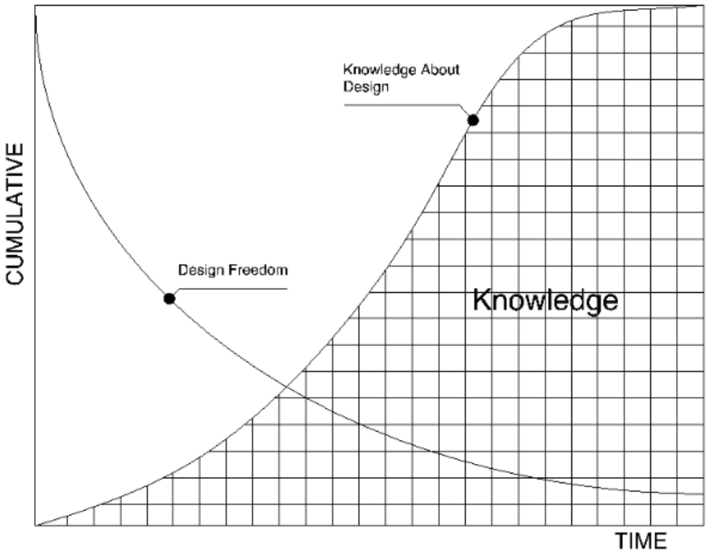


Fig. 2: Process knowledge

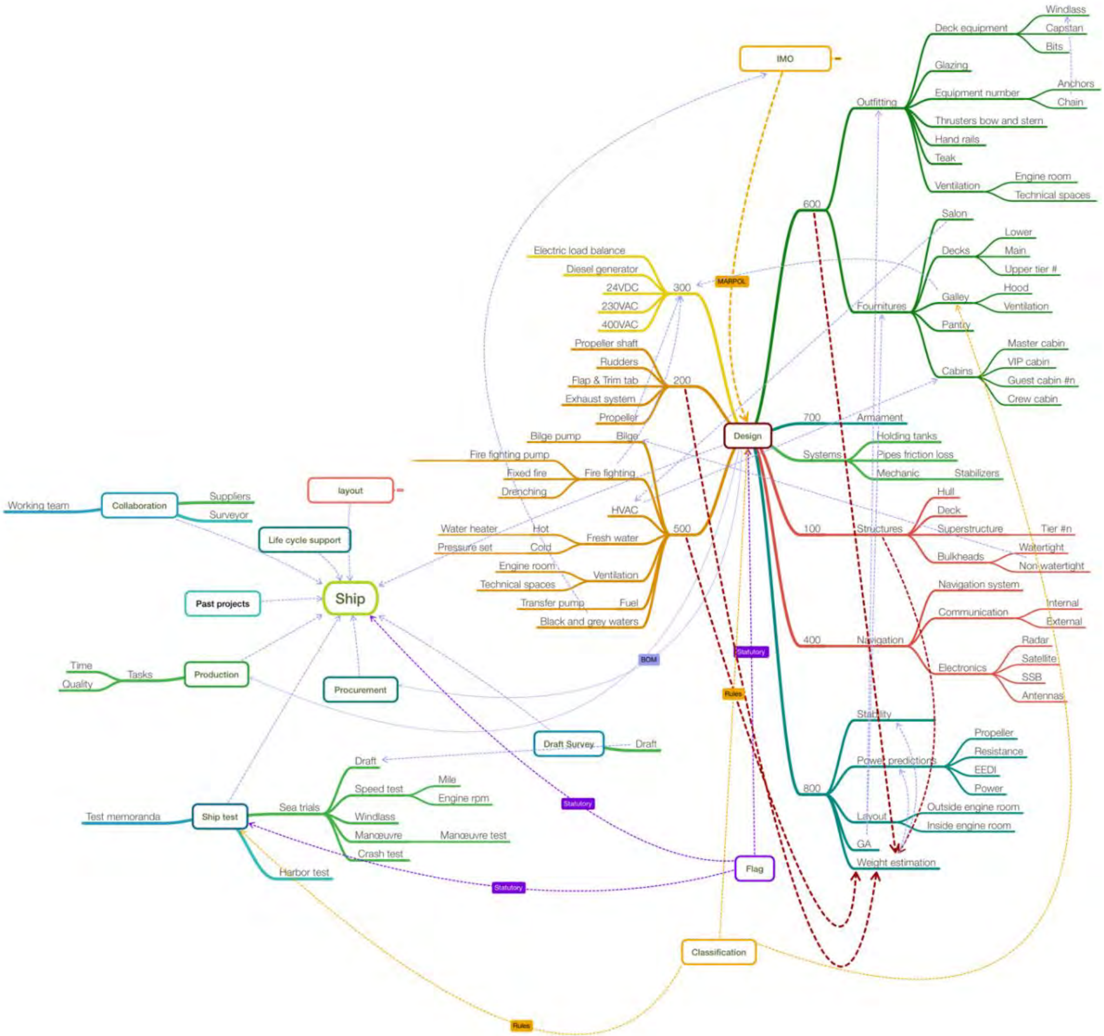


Fig.3: Ship mental map, showing interactions, simplified representation

Once described the ship with all her interactions and interdependencies we need a way to gather the knowledge encapsulated in the process. In the following, a way to collect and use this knowledge is described.

3.2 Field of application

The ship life cycle starts with a Client who provide a ship specification, he invites shipyard to respond to tenders or simply buy the product (for leisure, defense, professional tasks) and it ends with the hand-over of the good, i.e. the ship, to the Client.

Fig.4 shows the stages where the proposed tool comes in. The detailed design is left to specialized Computer Aided Ship Design (CASD) software. Feedbacks from Operations and Maintenance O&M should be included, since the ability to propose assistance after ship delivery is an important factor during today's contracts negotiations and, more important, feedbacks form this stage will greatly increase knowledge gain as well.

By the tool it will possible to perform calculation, to schedule tasks, to collect data and to provide reporting.

For instance, at the beginning one can use the tool to prepare the technical/commercial specification, then it will be possible to perform initial scantlings and calculations. The BOM will be shared with the Procurement service or the purchasers will enter data after inquiring suppliers; Production will schedule tasks; Testing service will prepare and schedule the HAT and SAT; Operation will plan maintenance. All these tasks can be concurrently done and shared among the actors.

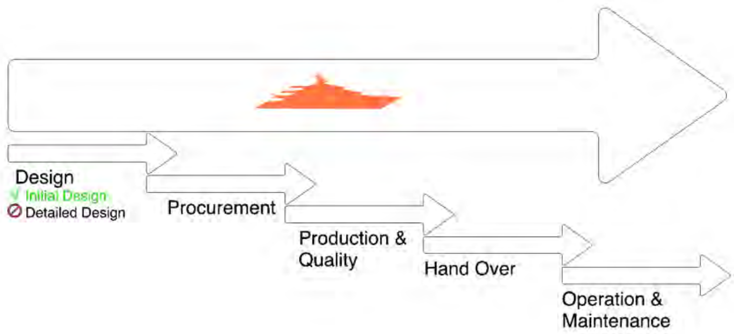


Fig. 4: Application life cycle

3.3 The Object-Oriented Programming and coding

The application uses the OOP Object-Oriented Programming approach, the OOP is a programming paradigm where it is possible to define data types which contain functions and variables. A feature of this data types is that they can be accessed and have access to other data types with which they are associated; so, data types can interact each other.

The two main actors of the OOP paradigm are class and object. Some OOP concepts:

- Class: A user-defined prototype for an object that defines a set of attributes and methods that characterize any object of the class.
- Class variable: A variable that is shared by all instances of a class.
- Inheritance: The transfer of the characteristics of a class to other classes that are derived from it.
- Instance: An individual object of a certain class. An object that belongs to a class Circle, for example, is an instance of the class Circle.

- Instance variable: A variable that is defined inside a method and belongs only to the current instance of a class.
- Object: A unique instance of a data structure that is defined by its class. An object comprises both data members (class variables and instance variables) and methods.
    - The behavior of an object is defined by its methods, which are the functions and subroutines defined within the object class. Without class methods, a class would simply be a structure. Methods determine what type of functionality a class has, how it modifies its data, and its overall behavior;
    - Attributes are characteristics of an object. Just as methods are functions defined in a class, attributes are variables defined in a class. Each method in a class definition begins with a reference to the instance object.

So, a ship is a real-life object which can be modelized to be a class according the OOP paradigm; it will be a software object ready to talk with other objects by accessing its attributes and methods. By describing the ship as a class, it will be possible to describe any ship using inheritance, Fig.5.

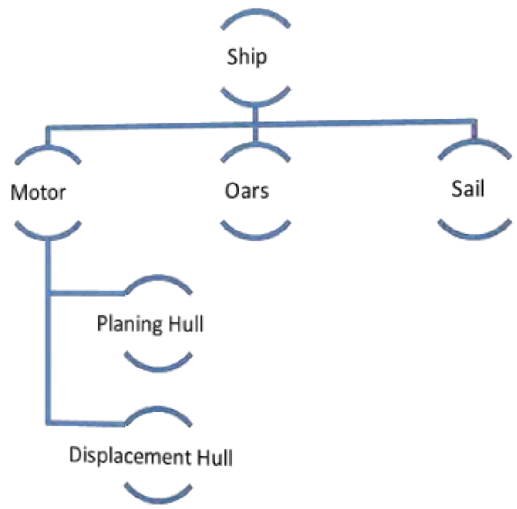


Fig. 5: Class, possible example for a ship

The use of OOP allows data attributes to be accessed so that it will be possible to:

- Get and set links among systems and sub-systems
- Get and set links among disciplines
- Refresh the KPI Key Performance Index
- Obtain reporting

The mental map in Fig.3 showed what I call the ‘process domain’, different from the ‘real domain’ where the ship is operated and she has interactions with the world and the users. Besides the two domains, we have also the ‘software domain’ where the ship is modelized by classes.

We can resume the Fig.3 saying that each single part will be:

- Selected -> Design phases
- Purchased -> Procurement
- Installed on board -> Production & Quality
- Commissioned -> FAT HAT SAT
- Operated -> O&M

We need a link among the above stages to address these interactions.

The UML (Unified Modeling Language), *Booch* (2005), language gives us a tool to do so, Fig.6.

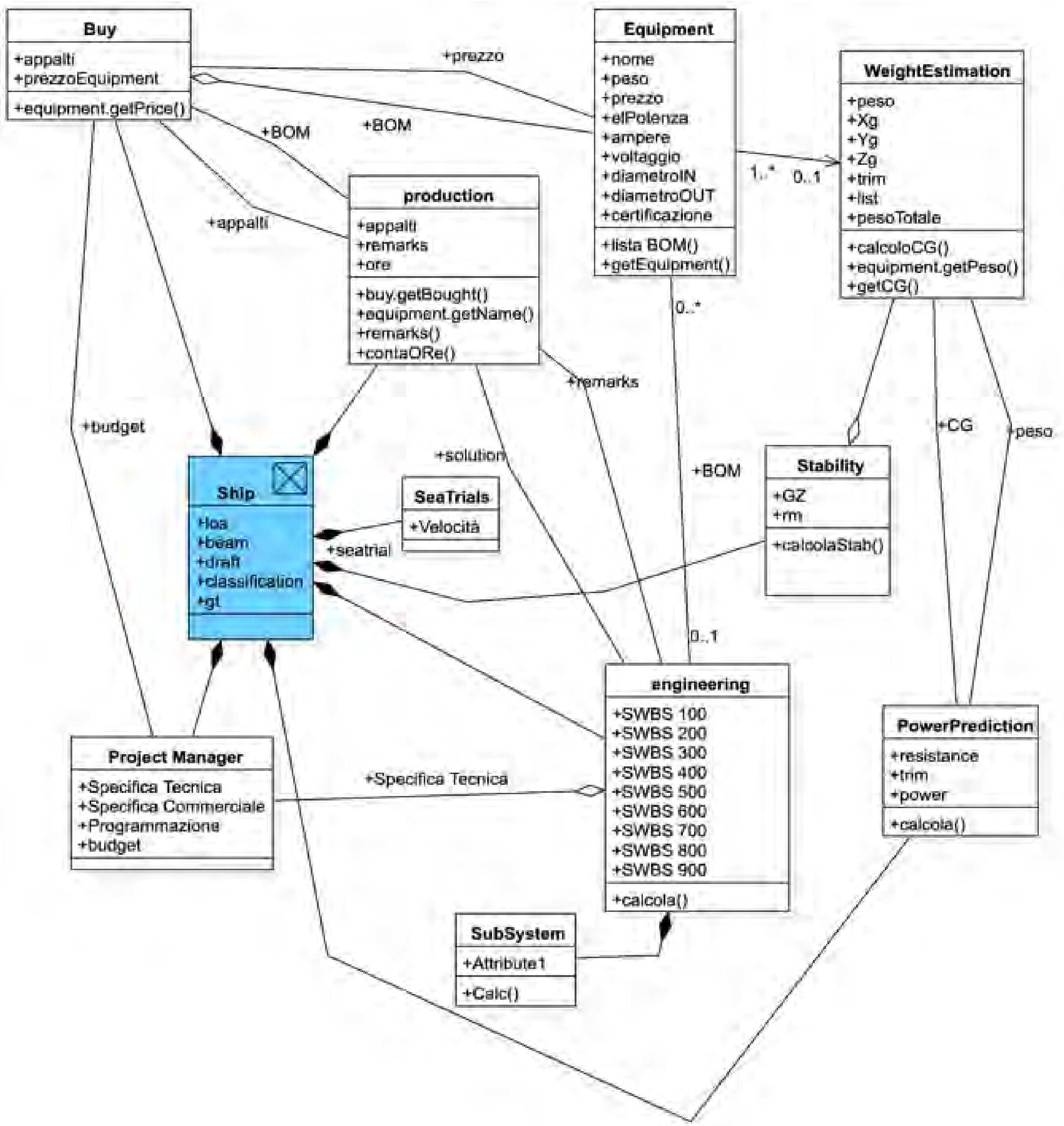


Fig.6: A possible UML representation of SHIP (UML created with StarUML, https://staruml.io)

UML is a powerful object-oriented methodology to describe features, activities, and states of a system and is frequently used in the process of software design. Object-orientation concepts describe systems as they are. Classes are identified and then interactions among those classes are modelled. This feature makes it possible to make a through-going design of the simulation model, *Kim (2005)*.

We can transpose the mental map in Fig.3 from the 'process domain' to the 'software domain', a more suitable way to describe the process and helpful in the development of the code. In the UML diagram we model the interactions among the different classes. We can establish all the interactions, dependencies in the software domain and so obtain the ship software description and then translate this picture in computer code. The UML has many different ways to describe how classes are connected:

- Association: two classes that communicate each other
- Composition: implies a relationship where the child cannot exist independent of the parent. Example: Ship (parent) and Cabins (child). Cabins don't exist separate to a Ship.

- Aggregation: implies a relationship where the child can exist independently of the parent. Example: Ship (parent) and Engine (child). Delete the Ship and the Engine still exist.

With these concepts we can model our process in the software domain.

3.4 Persistent storage

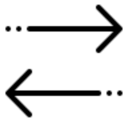
To get the holistic approach, a dialog among the different systems and subsystems is necessary. The UML representation gave us the possibility to describe 1) the 'ship domain' from a code point of view and 2) the relationships in the 'software domain'. Attributes and methods alone do not suffice to obtain the reuse of experience; we need to make information persistent, data will outlive once the user quits the tool. To obtain data persistence, the proposed tool uses a logical representation of data that allows information to be accessed without consideration of its physical structure, in other words: a database. The database lets the tool to perform queries (i.e., to request information that satisfies given criteria) and to manipulate data. Data are stored in tables with rows and columns. Each table column represents a different data attribute, while rows are unique within a table, but particular column values may be duplicated between rows, *Deitel and Deitel (2015)*.

The OOP methods and the persistent storage allow the application to inform the user, everywhere and at any time, about the process.

Table I: Persistent storage

				
Class/object		Object Storage		Database

Table II: Fetching information from the data base

		
Devices	Insert / Query	Database

An example of database table:

```
CREATE TABLE Customers (
        Id          ShipID      NOT NULL PRIMARY KEY,
        Name        ShipName    NOT NULL,
        LOA         ShipLOA     NOT NULL,
        ….          ….          ….
        FLAG        ShipFlag    NOT NULL,
        ….          ….          ….);
```

We can perform different operations (= queries) using the database, *queries* specify which subsets of data should be selected from a table:

1) Retrieve a ship from the database using the ship's name
   a) **SELECT** *ShipName* **FROM** *tableShip*
2) Retrieving a ship from the database using the ship's name with a criteria to be satisfied
   a) **SELECT** *ShipName* **FROM** *tableName* **WHERE** *ClassificationSociety = 'DNV - GL'*
3) Retrieving all equipments from the database using the SWBS criteria
   a) **SELECT * FROM** *tableEquipment* **WHERE** *SWBS = '500'*

4) Update a *specified table*

a) **UPDATE** *tableName* **SET** *columnName1=value1*, *columnName2=value2*, *...*, *columnNameNth=valueNth* **WHERE** *criteria*

b) **UPDATE** *Ships* **SET** *ShipClassNotation = '1A Yacht PY3'* **WHERE** *ShipName = 'Simon'* **AND** *ShipFlag = 'CISR'*

5) Delete from a *specified table*

a) **DELETE FROM** *table** **WHERE** *criteria*

Doing so we will be able to update the KPIs and to access the needed information during the use.

3.5 The structure skeleton

The project subdivision in simpler process and the hierarchical structure simplify the process management and control. The structure is split in groups and sub-groups and each group is defined by function. This breakdown considers the complete product/ship life cycle to organize and correlate costs, weight, specifications, systems, operation and maintenance.

Among the different breakdown possibilities, I mention only two here:

- U.S. Navy Expanded Ship Work Breakdown Structure (ESWBS),
- SFI group system MARINTEK (former Norwegian Ship Research Institute (Senter for Forskningsdrevet Innovasjon - SFI).

In the ESWBS breakdown, groups are split by function, in Table III the principals from *Pal (2015)*.

Table III: ESWBS from *Pal (2015)*

ESWBS Group	Description
000	General Guidance and Administration
100	Hull Structure
200	Propulsion Plant
300	Electric Plant
400	Command and Surveillance
500	Auxiliary Systems
600	Outfit and Furnishings
700	Armament
800	Integration/Engineering
900	Ship Assembly and Support Services

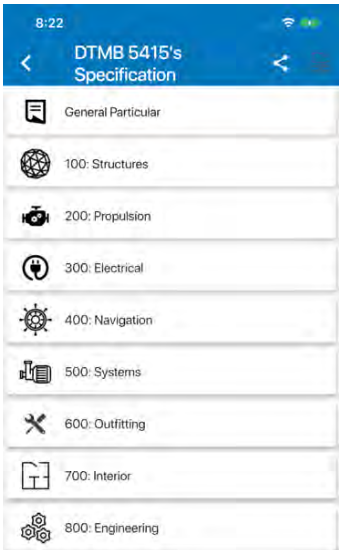


Fig.7: Breakdown structure skeleton

I use the ESWBS for the application because it is widely used and proven in the industry and because of author familiarity with the model. The structure breakdown in the application can be displayed in Fig.7. The structure groups the tasks giving to the user a scheme to follow.

3.6 User Interface

The hierarchical structure, shown in the previous chapter, is exposed to the user to interact with the application in the way she/he likes the most, jumping from one task to another or recalling *Nowacki (2016) "The sequence of steps in developing the product model is in principle arbitrary. Whenever the information is incomplete for performing a certain step, it must be substituted by provisional, assumed or approximated data. Thus the product model is open to overlapping concurrent engineering actions."* The user interface (UI) allow the operator to fill in the fields with input data or the UI will show data retrieved from the data base when available. In this way the user will have the choice to proceed as needed. An example will be shown later.

3.7 Data entering

To provide or report information about the KPIs and the project status it is necessary to perform calculations or estimates and enter data. *Ebrahimi (2018)* shows that a compromise between the accuracy and the rapidity of response must be found; in addition, it is reported that empirical equations provide a computational accuracy, depending on the project, of about 80% compared to tests.

The source of the equations used in the application comes from:

- Rule of thumbs, coming from experience
- Regressions
- Engineering and technical literature
- Classification and statutory rules or scantlings

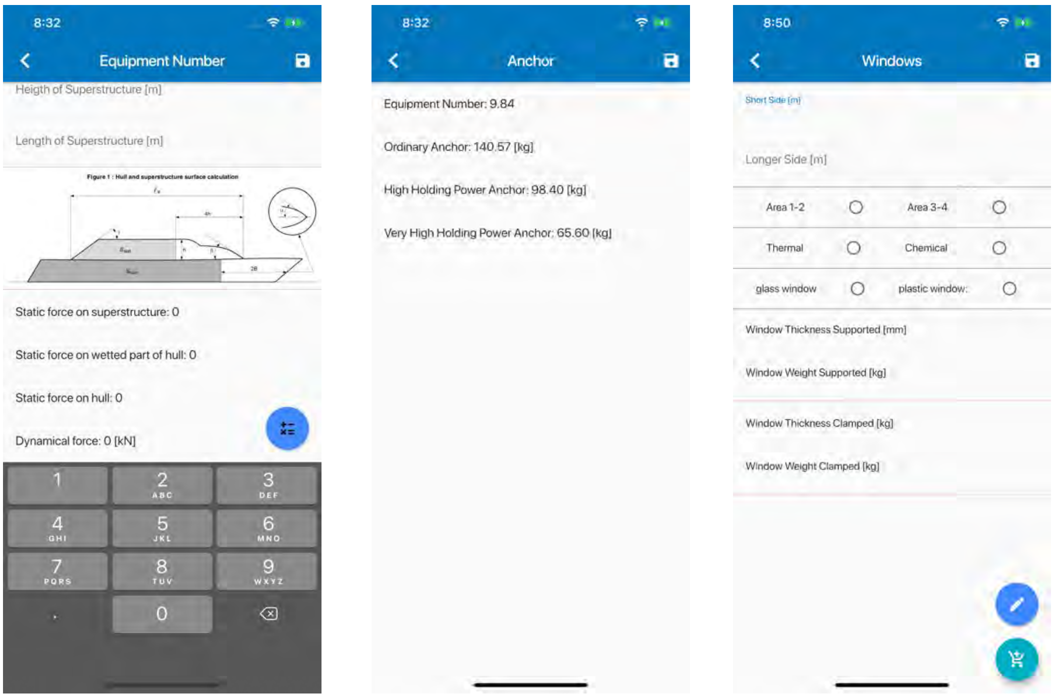


Fig.8: Hypothetical value of anchor weight and equipment number and Hypothetical glazing calculation

Fig.8, as an example, shows the calculation of the weight of an anchor; once the Equipment Number (EN) is fetched from the database, the anchor weight can be automatically calculated (in this case using the Bureau Veritas rule). The EN has been previously calculated (Bureau Veritas rule) and stored in a dedicated variable and in its reserved row in the data base table. The Bill of Material, weight estimation and budget are updated without any direct action by the user. The two data are from different SWBS; in case the EN is not known, the user can use the knowledge from the experience of past projects, which has been collected and injected in the application, to estimate the value and obtain the weight of the anchor. If information is not available it is possible to enter data in the relevant field and continue the process without waiting for the information to come or go to collect it. In this way we can have an almost arbitrarily experience and a more concurrent environment is obtained.

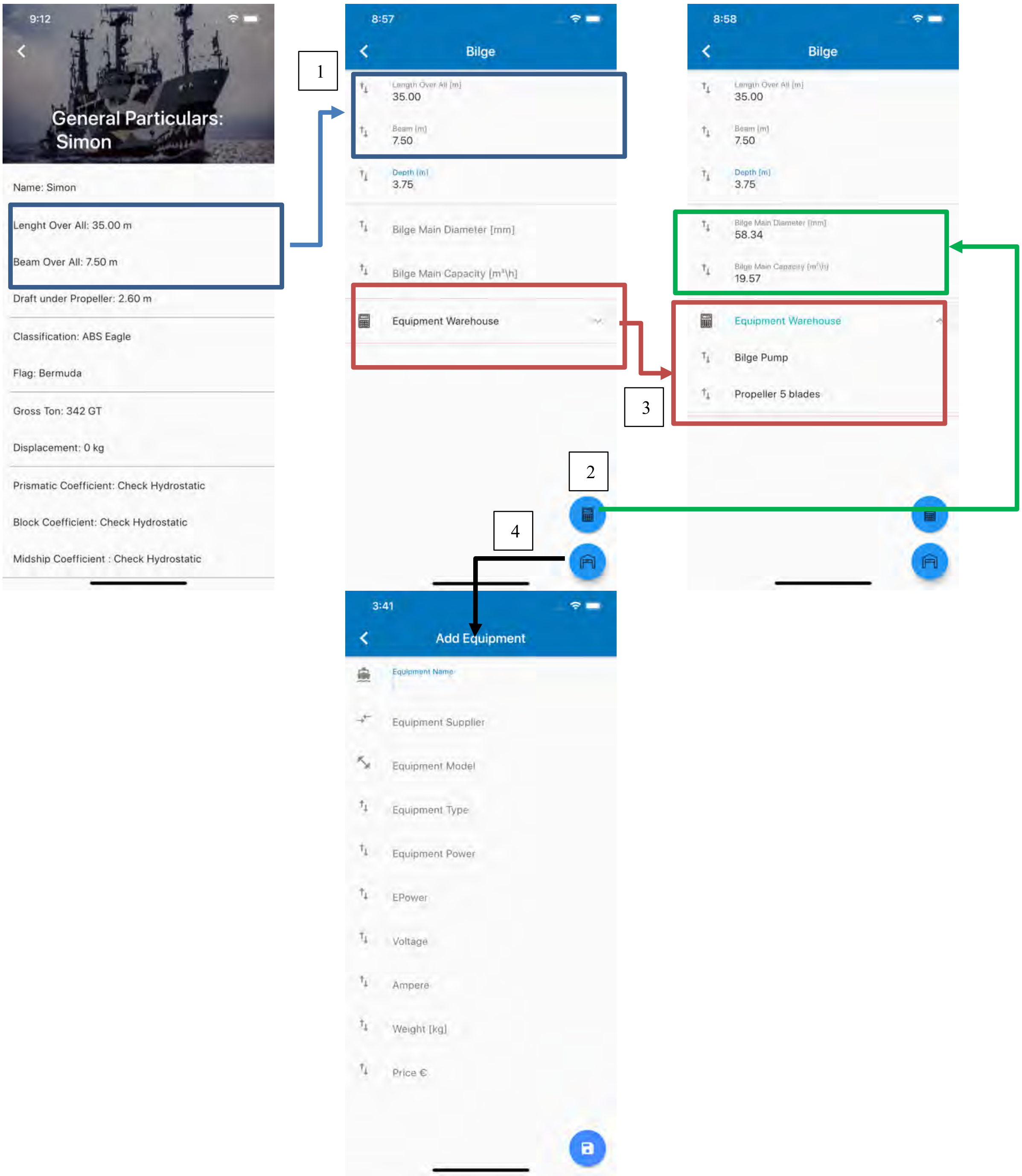


Fig. 9: Example of calculation path

Another example could be the calculations for a glass pane, Fig.8. We will have the possibility to make estimation which could be used for early price approximation in order to obtain glass costs from a supplier or an estimate of its weight to update the preliminary weight estimation and KG position.

Classification rules have been used so far, but we could use regressions or other sources to compute data as well. For instance, we could use Savitsky's empirical method to calculate the resistance and hence the required power and trim or regression methods as the Radojčić one, Wageningen data for propeller, etc.

We are harvesting data (= knowledge) along the process and we store information for future use.

Fig.9 shows the calculation path for a hypothetical ship's bilge system.

> 1: Values are automatically uploaded in the relevant fields from the data base (if values are not known, or not yet calculated, the user can input the pertinent data)
> 2: The button launches the calculation
> 3: The list shows the equipment in the database to retrieve an apparatus already used.
> 4: If any equipment at point 3 satisfies the user, it is possible to create a new equipment

The BOM (Bill of Materials), Budget and the Weight Estimation, among the possible KPI, are instantly updated, Fig.10.

This will help to take decisions and to influence in the process earlier, as all the forthcoming decisions will have to adapt to what have been previously decided and so the later choices will have less influence on the total cost and performances.

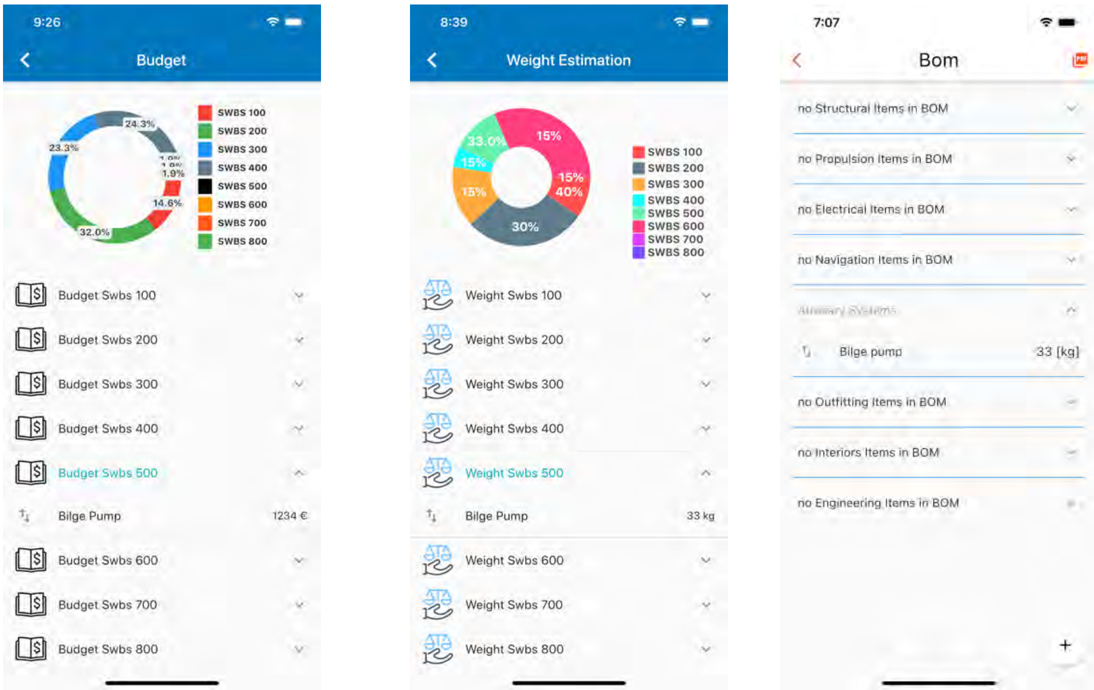


Fig.10: Budget, Weight and BOM

I lingered on the Design stage, this because this phase best captures the interactions among the systems and because it is helpful to show the use of the database. The proposed tool aims to cover the full ship life cycle. To do so we need to address other disciplines as well.

The starting point for the Purchasing service can be the BOM obtained from the Design Office; another entry point can be the Client desiderata detailed in the technical specifications or in the contract. In both case the interactions between Design and Purchasing, in the proposed application, will be managed by the database. Doing so the BOM is accordingly updated and the Budget as well. So, if the purchasing has the priority over the Design, the database will serve the information to the design team. We are able to obtain coordination between the two company services.

We do not collect information only designing or purchasing equipment, we gain knowledge from the feedbacks coming from Production as well. We will be able to manage:

- the "production states", i.e. the conformity or not of an equipment or of a general action performed during the ship building

and

- the "production records", i.e. the list of jobs with its allocated time.

Not only the feedbacks from the production are important but also the ones coming from the Operation & Maintenance (O&M). This is the period where the ship is operated and all the choices made are validated. Again, the feedbacks form the O&M are fundamental for the comprehension of how the ship is used and how each equipment performs. I utterly believe that feedbacks from the field (Production and O&M) are a valuable asset during the design phase. Then the ability to determine the O&M needs earlier gives the possibility to set a strategy to maintain the ship in operation readiness.

Finally, documentation can be created automatically, as per Fig.11, fetching data from the database.

Fig. 11: Technical documentation

4. Why portable device?

The use of collaboration tool running on personal device is already widespread today in every context, from personal to enterprise environment. Shipyards are faced to hard competitiveness with short delivery times and tight budget. The market is global and time spent out of office to visit Clients equals or exceeds the time spent in workplace. The need for real time data is of paramount importance. Shipbuilding process must be agile so shipyards will be able to modify strategy according to the needs. Shipyards, using this kind of tool and device, will be able to connect quicker with staff and partners. They become more agile and they will work smarter by having unified communications and easier access to documents.

5. Conclusion

This paper introduced a tool that let shipbuilders to be agile, flexible in their business model and strategies to effectively face or respond to market instability.

This instrument is holistic and uses a concurrent engineering model. The shipbuilding process is considered as a whole and there is not, necessarily, a predefined path to follow. This is obtained by the use of oriented-object programming and database. Object-oriented programming allows the link between the different ship services that are modeled as classes; the database allows the collected data to outlive and, so, to be reused and makes possible the communication among the ship services in the software domain. The data collected is the knowledge of the process that we acquire during the usage of the tool. The use of personal devices provides a flexible device where visualize the KPIs of the process and a way to experience meaningful collaboration, to improve communication, to increase productivity and to facilitate the research of information.

Acknowledgement / Statement

The statements contained in the paper reflect solely my opinion, based on my personal research and working experience as mechanical and naval systems engineer in yacht yards as Sanlorenzo, Azimut | Benetti, Palmer Johnson and CNC Chantier Naval Couach among others and propulsion system provider as France Hélices; I, today, hold a permanent contract at Technifrance SA. Besides myself, no one else (natural person or legal person) has been involved in the conceptual work exposed in this paper and in the programming of the application. To the best of my knowledge, no other person (natural or legal) has developed a similar concept at the time of writing and sending this paper to COMPIT 2021.

The work exposed was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Artificial Intelligence Entering Maritime CAD/ CAM

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Abstract

Although artificial intelligence has become an everyday topic, it is still a challenge to apply this technology to Maritime CAD. Inside AI, different technologies, such as Machine Learning and Deep Learning are taking an increasing protagonist in shipbuilding. This paper will provide a general overview of AI regarding the Maritime CAD industry, aiming to establish the advantages that these provide to our industry, and providing explicit use cases on the matter

1. Introduction

Artificial Intelligence (AI) has entered our lives stealthily but like a whirlwind. AI is becoming a reality in many fields of the common life. The way AI is entering our ordinary life is well known or should be. Many of the agents anyone contact for help through help desk is drive by the AI. Many of the information we access through the web is oriented by our previous navigation records. Results of the requests to medical, finance or legal services is obtained through AI engines that become final decision makers. However, many people tend to think that AI is simply there, available to anyone and to do everything that involves an effort for those who have to do it. Gathering requirements for final CAD users, they claim to have automatic tools that using AI make the designs that they would do. That is, they do not want an AI but an AI that thinks exactly like them. The reason is a misinterpretation of what AI is and what it can do. Therefore, it is necessary to make it very clear what AI is and how far it can go today.

We can assume that AI is “a combination of algorithms planned with the objective of creating machines with the same capacities as humans”. And, what capacities are those? We can accept there is a consensus that the basic capabilities should be the following:

- To act as humans do.
- To reason as humans do.
- To reason rationally.
- To act rationally.

AI is supported by several pillars that together allow to get value of this disruptive technology. But in turn, each of them can represent a challenge to be able to apply it to the different fields of activity of the human being. These main pillars are:

- Data algorithms.
- Big data and data science.
- Computing machines.
- Machinery supervising.
- Human beings.

Applying AI to use cases related to CAD requires that the pillars of AI can be sustained in those cases and that the capabilities that are intended can be achieved.

We will review some of the aspects involved in this issue, such as the requirements demanded by marine CAD users, possible applications to aspects of the workflow of the marine shipbuilding, specially focused on the marine design and the tools used and the application limitations in this particular industry.

2. Practical approach

To understand how AI could be applied to some aspects of using marine CAD, it is important to have end users in place from the beginning. It is about knowing in detail the expectations they have and at the same time explaining what is possible, what is not and why. One recurrent mistake that should be avoided is the tendency to choose a certain technology and try to adapt it to any type of problem. This causes the ultimate goal of work to be forgotten, focusing exclusively on the technology that becomes the objective, when it should only be a way.

This work can be done with different approaches. At SENER, we opted for "design thinking" workshops, where we try to recognize the role and the job of end users, how they work and what are the most relevant elements of the processes they use to design ships.

“Design thinking is a term used to represent a set of cognitive, strategic and practical processes by which design concepts (proposals for products, buildings, machines, communications, etc.) are developed. Many of the key concepts and aspects of design thinking have been identified through studies, across different design domains, of design cognition and design activity in both laboratory and natural contexts”, *Muñoz and Pérez (2017*).

This methodology starts by understanding who the customers are, following by the customer needs, their journeys and their problems. This business is clearly customer oriented or should be so, understanding all these aspects it is possible to build solutions that really address the problems, either using AI or not. The results allowed us to identify some of the practical applications of AI. The work stages are as follow:

1) Defining the person for whom the solution is intended.
2) Understanding what their work and environment are like (empathy diagram).
3) Understanding how users do their job and how they get the information they need to do it.
4) Describing user’s activity at work.
5) Identifying problems they are facing.
6) Describe the structure of the work and the fitting of people in it.
7) Extracting the demanded requirements.

The workshops were performed with people from several shipyards and the methodology was duly applied. People were divided into different groups and conclusions were shared at the endo of each session. Fig.1 shows an image of the “Persona” diagram can be seen.

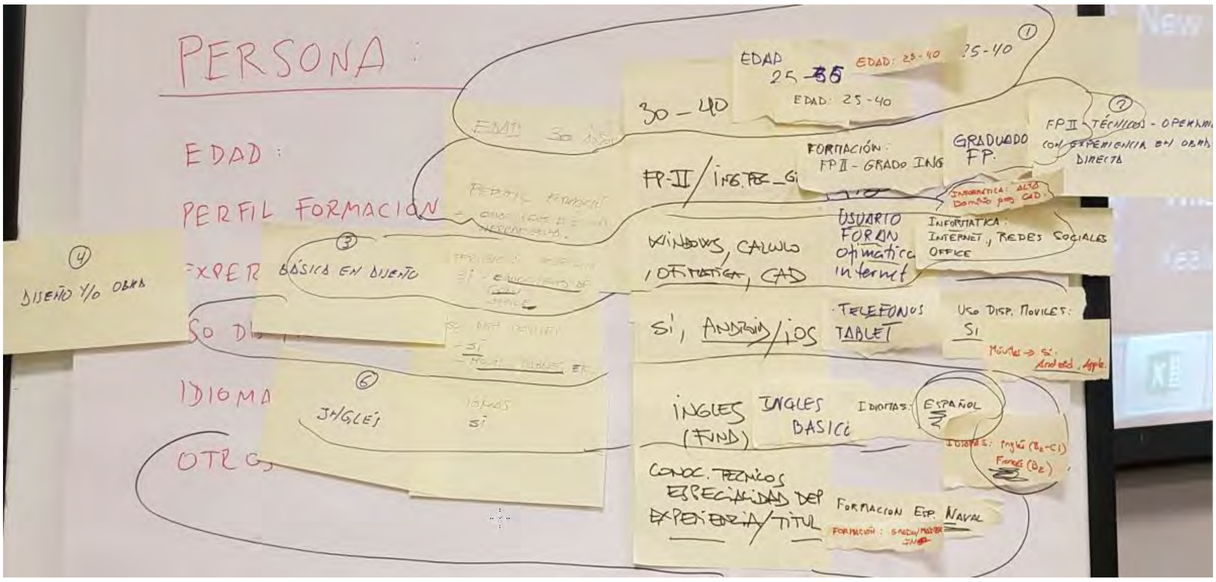

Fig.1: Diagram of a Person

Following the most relevant needs or requirements demanded by users after the workshops are enumerated and described.

2.1. Technical Virtual Assistant

Users explained the difficulty in mastering the new technologies and CAD itself, since their use was increasingly complex. Help tools were insufficient or outdated. They considered necessary to have a system that would provide them with the precise and updated information to do their job. This information was not only how to manage the system, but also how to do it efficiently, complying with the organization's design rules and with the regulations applicable to shipbuilding.

In addition, users wanted an easy interaction with the system, so they could easily express themselves in the usual vocabulary of their work.

2.2. Minimizing design errors

One of the main concerns of users was related with the difficulty to detect errors in the design. Many times, errors are not detected until the parts are to be fabricated, or even when they are already built. This situation causes delays and sometimes material waste and an increase in cost. In addition, the later the problem is detected, the greater the cost of the solution from all points of view: money, time, and functionality.

The users demanded a system that warned them of possible errors that could be committed or at least some method to identify them before the designs were delivered from the technical office to the workshops. Ideally, the system should work in real time, but it was understood that this way of working could have negative impact in terms of performance, since the system could be slowing down during normal daily work and, however, the mistakes that could be made, although provoking serious consequences, may not be abundant. In other words, a one-time post analysis, versus continuous real-time analysis, might be sufficient.

2.3. Automated repetitive tasks

One of the ways to save detail design time is to automate repetitive tasks. To carry out this automation, there are already systems that allow the elaboration of macros or scripts that automate a certain job. However, doing these scripts requires programming skills that normal users do not have. Therefore, they would want a system that provides them the identification of the repetitive work and the creation of the macro or script corresponding to that precise work. So, the topic comprises two steps: identification and creation.

Another use case described by the users could be the auto filling of parameters for definition of components of the design. Some components need to fill many values for the design parameters. These values may be like most of the components but not always the same. It is expected that using AI the system could select the most adequate values for the design, considering the project, and additional criteria like design rules, optimization calculation, etc.

2.4. Automatic recognition of models

One of the business opportunities in the field of shipbuilding is related to the retrofit of ships. For this work, the ship is scanned and the images, or cloud of points obtained are used for creating the CAD models wherever is possible or taking geometrical data to locate models created in external tools. However, the analysis of the images needs a human being to interpret them. This task is extremely time consuming and it is sometimes more appropriate to start a model from scratch. Often, users think that AI should be able to work with those images to create the models that they represent.

2.5. Model and building review

The model must be reviewed to ensure that the design meets the requirements of the project. This review includes a wide catalogue of requirements that materialize in designs modelled in a virtual environment of geometric models. For each of which it is necessary to find how the requirement is fulfilled. This laborious work requires a follow-up and matching of concepts. To facilitate this work and ensure that requirements are not lost, a system is required to support requirements traceability.

The building needs to be reviewed. It is needed to provide an automatic review system for design quality check. There are a large variety of concepts that must be reviewed, for example, to check for missing components like hull reinforcement, outfitting hole reinforcement, block boundary, stealth requirements, tank class rule scantling, steel grade, etc… This task can be made manually but is subject to human mistakes. Being a very laborious work, it is thought that it is possible to find methods in which the AI can do the same work systematically and without errors.

2.6. Cost estimation

Cost estimation can be made by using several estimation techniques. Among these techniques, following can be considered: analogous estimation, parametric estimation, bottom-up estimation, etc. All of them are based in extracting regressions from wide range of data. The regression formulas obtained can be updated with new values. A more dynamic update is desired with new results from current projects and with update contextual values. However, keeping the formulations up to date is very expensive. It is reasonable to think that AI could add a lot of value to adapt formulations to the current context. In particular, machine learning college can be of great interest.

2.7. Initial designs

Conceptual project for a ship is largely supported by correlations that could be very well supported by AI. Based in similar projects already developed AI should be capable od predict the parameters of new projects or designs.

3. AI Concepts

Before being able to affirm that these problems or at least some of them can be solved by AI, it is necessary to know minimally the fundamental elements on which this "new technology" is based and then determine to what extent these problems can be solved with AI. or not. Although AI is often talked about, this concept is encompassed in a broader one that is data science, also known as Big Data and Analytics. Fig.2 shows the general understanding of different technologies and the relation among them.

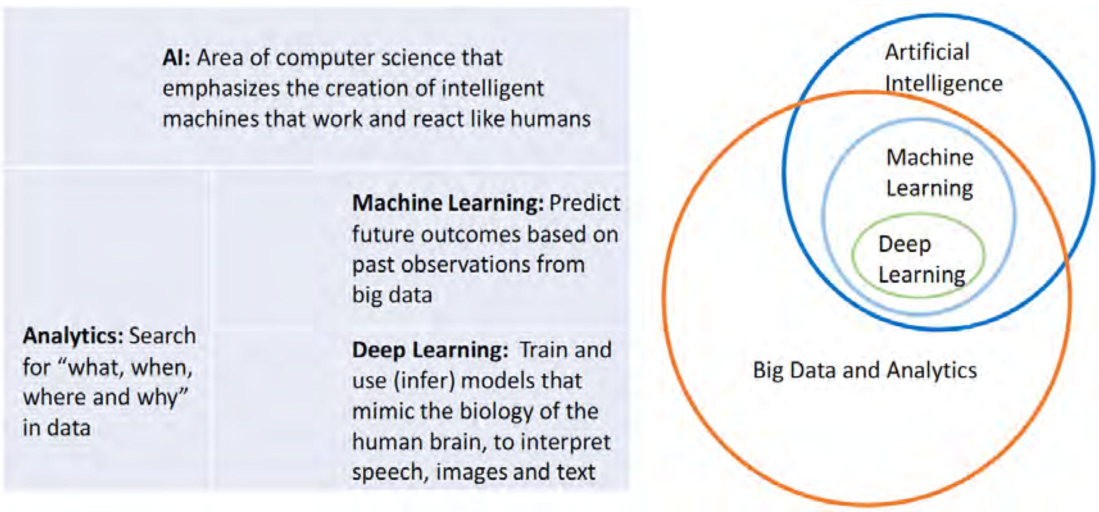

Fig.2: Conceptual map of AI, ML and DA, *Kirkpatrick (2018)*

Here we can see more clearly that AI is just one part of a science that, when applied well, has become a technology in its own right. Let's see, then, in a little more detail what each of these pieces are, because it will allow us to better understand to which problems this technology can be applied and to which it cannot.

3.1. Artificial Intelligence

Despite being born as the idea of creating machines capable of simulate human behaviour, AI has evolved to comprise multiple mathematic techniques used in computing and essential to create this "intelligent" machines, sharing a great number of concepts with data science.

3.2. Data Analytics

Data Analytics (DA), also known as Data Mining, is the discipline dedicated to analyse data to establish relations and provide conclusions. The extraction and preparation of data is essential to work with and it is included in this field of study.

3.3. Machine Learning

Machine Learning (ML) allows the extraction of patterns from a data set. There are different types of analysis on this field, such as data clustering, support vector machines, association rule learning, Bayes algorithms, and all other algorithms included in DL. ML is the evolution of ruled based systems, being able to distinguish among valid and surplus data, as well as deducing new rules not previously programmed. Fig.3 shows the components and relations of the most relevant topics related with ML.

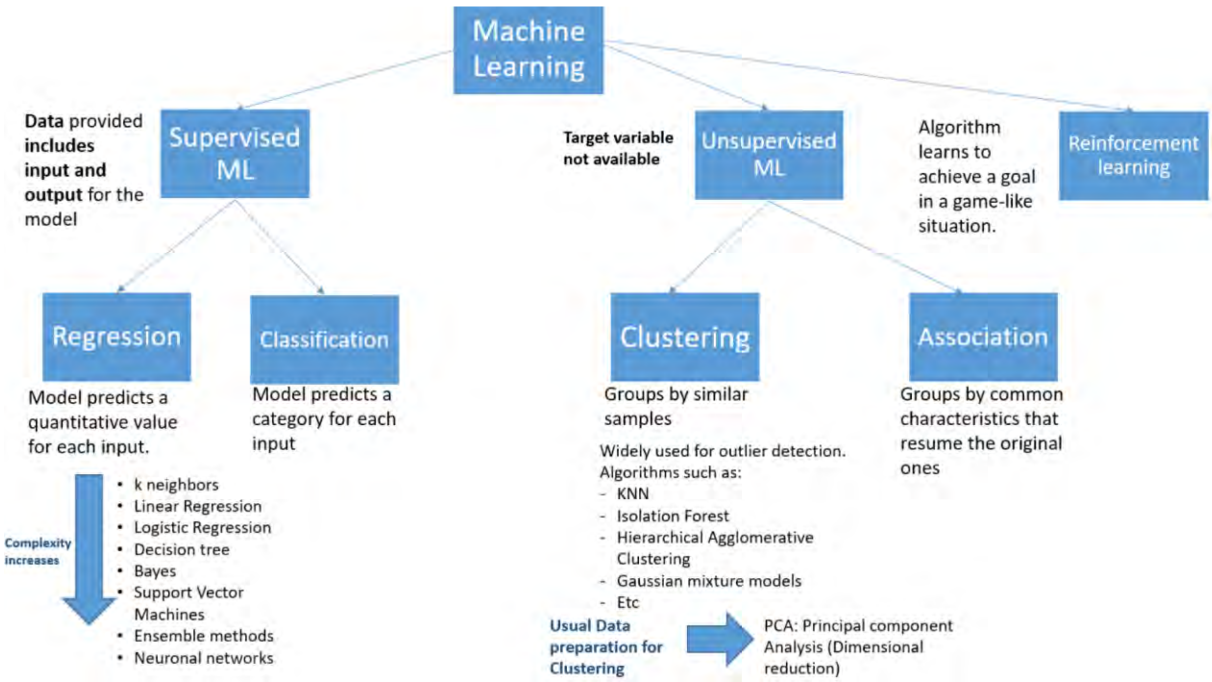

Fig.3: Components and relations of the most relevant topics related with ML

4. AI entering in CAD/CAM/CAE

A correct understanding of what AI is allows us to conclude that to apply AI to CAD users' problems it is necessary to have the following elements.

It is necessary to understand what the problem is. It is not the same to check that a model is correctly designed than to obtain a cost prediction model from a design. The common base is the data, but the different objectives make it is necessary to use different algorithms and different preparation of the data. As it was stated in *Ramírez et al. (2020)* that "the use of these technologies requires the existence of algorithms, which are previously built with data. These can be generic, available for any industry or business; or specific, those corresponding to a particular industry, a shipyard or technical office. Due to the specificity of the marine industry, from our point of view, generic data will not be of much use for the design of particular shipyards or technical offices want to do. On the other hand, specific data of a design is not usually shared by shipyards and technical offices, since it is what gives them value and allows them to differentiate themselves from each other. This leads us to conclude that to have AI tools, the shipyard, office or naval designer, will need to create their own algorithms based on their own data".

To ensure the correct selection of the algorithms, it is necessary to have adequate criterion to determine the correctness of the results obtained. This means that the team preparing the AI engine must have knowledge of marine concepts and marine engineering criteria. Due to this fact, to obtain algorithms that provide valid results, it is key to have a professional data analyst or technical profiles that can distinguish between different technologies and the best way to apply them.

The data to be used needs to be well prepared. This is the "Data Mining" stage. This stage is essential to obtain meaningful results. But also, it is essential to have a lot of data, so that the ML can work, and the results could be contrasted.

One of the most used methodologies in this DM stage is CRISP. CRISP stands from Cross-industry standard process for data mining. This technique divides the process into six main processes, Fig.4, with a partially flexible phase sequence. According to this methodology, business and data understanding are key.

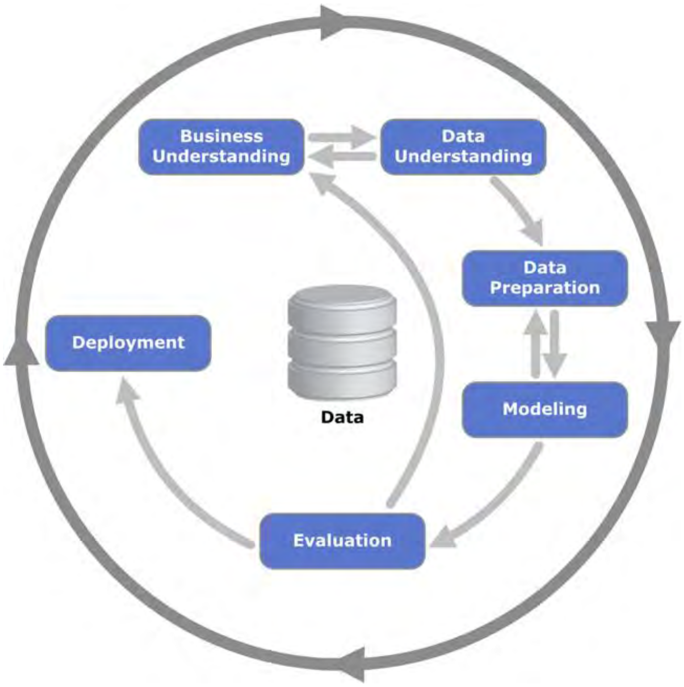

Fig.4: Diagram about CRISP Methodology, https://es.wikipedia.org/wiki/Cross_Industry_Standard_Process_for_Data_Mining#/media/Archivo:CRISP-DM_Process_Diagram.png

Once the AI engine is prepared is necessary to train the algorithms. This is to enter structured data into algorithms and indicate what are correct results and what other not.

When trying to apply AI to cases described in Chapter 2, some limitations appear. Main challenges are:

- Shipyards and Technical offices have a lot of data, but data are not structured nor even in an electronic format.

- There are not valid skills of workers capable to train the AI systems.
- Many processes acclaimed under this term are merely classical frequency studies or simple optimization problems, where there is no technology other than classic arithmetic.
- Shipyards and technical offices are reluctant to feed AI systems with their own data as they consider them as confidential.

When analysing the cases raised by users, it is obvious that some of them do not have the conditions that allow them to be handled with artificial intelligence techniques. In other cases, a classical deterministic optimization methodology may suffice. And in other cases, the AI models are so complex that it is not practical to integrate them with design tools that require rapid response in real time.

For these reasons we focused in three use cases that could be addressed without those limitations.

5. FORAN assistant

FORAN assistant is a cognitive system that gathers all the relevant information of the shipyards, technical offices, classification rules, CAD/CAM/CAE/CIM users guide, best practices documentation, practical use cases. The system is an AI powered by IBM WATSON© technology capable of understanding technical human language and providing the most adequate answer to the user's questions. The system learns for the reaction of the users and with the training with new information. With this system:

- Leverage experience, best practices, guidelines both in vessel design and construction stages.
- Optimize and harmonize design based on applicable design rules.
- Increase quality design by reducing errors.
- Speed design and construction providing expert assistance to designers from early stages to most complicated ones.

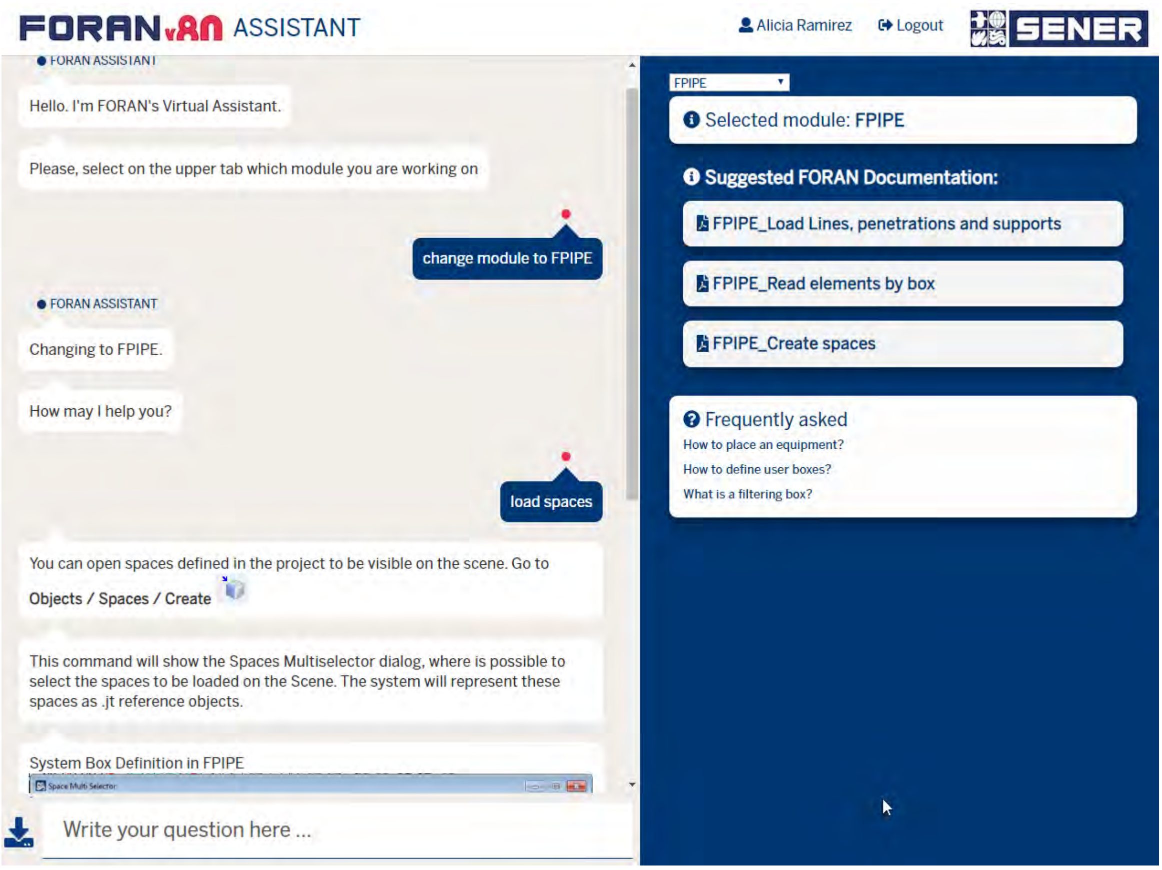

Fig. 5: FORAN Assistant Dialog Window

The system is presented like a chatbot interacting with the user and providing the most adequate information, Fig.5.

Shipyard and Technical offices competitiveness, increase accelerating the Ship Design Cycle and, as consequence, significant time to market and cost savings.

6. FORAN Insights

FORAN Insights is a set of algorithms of machine learning that work on a set of data extracted from the ship project. The data corresponds to parts designed with FORAN. The data are prepared to normalize the parameters used. FORAN insights analyses the values and presented to users to evaluate the consistency of the project. This methodology can be applied to different cases. We present here two of those use cases.

6.1. Outlier components

The system analyses the parts defined in the project and establish what parts are fitted to standard parts or standard parameters. So, those parts that do not fit with the standards could be a mistake or could be optimized to be standard part. The benefits are:

- Less time in design.
- Optimized results.
- Significant savings.

The analysis can be made to different stages of the lifecycle of the project. The system essentially does the following:

- Study data and detect outliers with Machine Learning Algorithms.
- Provide Project Insights Dashboard for decision making, Fig.6.

Fig.6: Dashboard of standard flat parts designed

6.2. Parameters prediction

Many components have a repetitive set of values to be defined. Normally, a ship will have a long list of piping components, but not all components will be used everywhere. For example, specific materials or diameters will only be used for certain fluids or systems. To limit the number of components available when routing a pipe, we define what we call Material Specifications (SMAT). A SMAT is like a filter that limits the possible components to be used, according to their attributes. For example, if we select a SMAT which only allows fittings with diameter between 25 and 50 mm, we won't be able to select components with a different diameter when that SMAT is selected. And the same with material, pressure, etc.

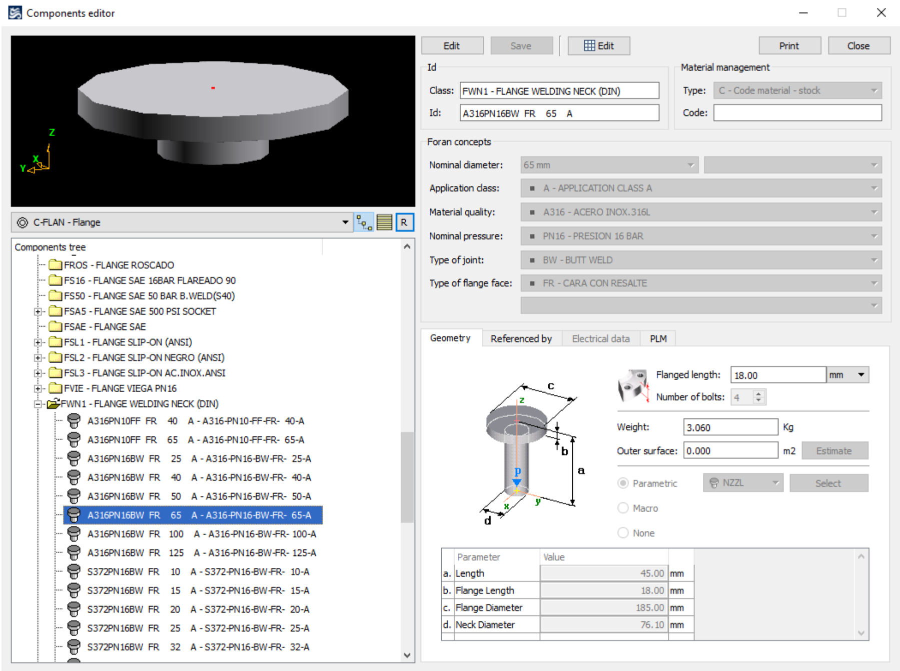

Fig. 7: Input data of Flange definition

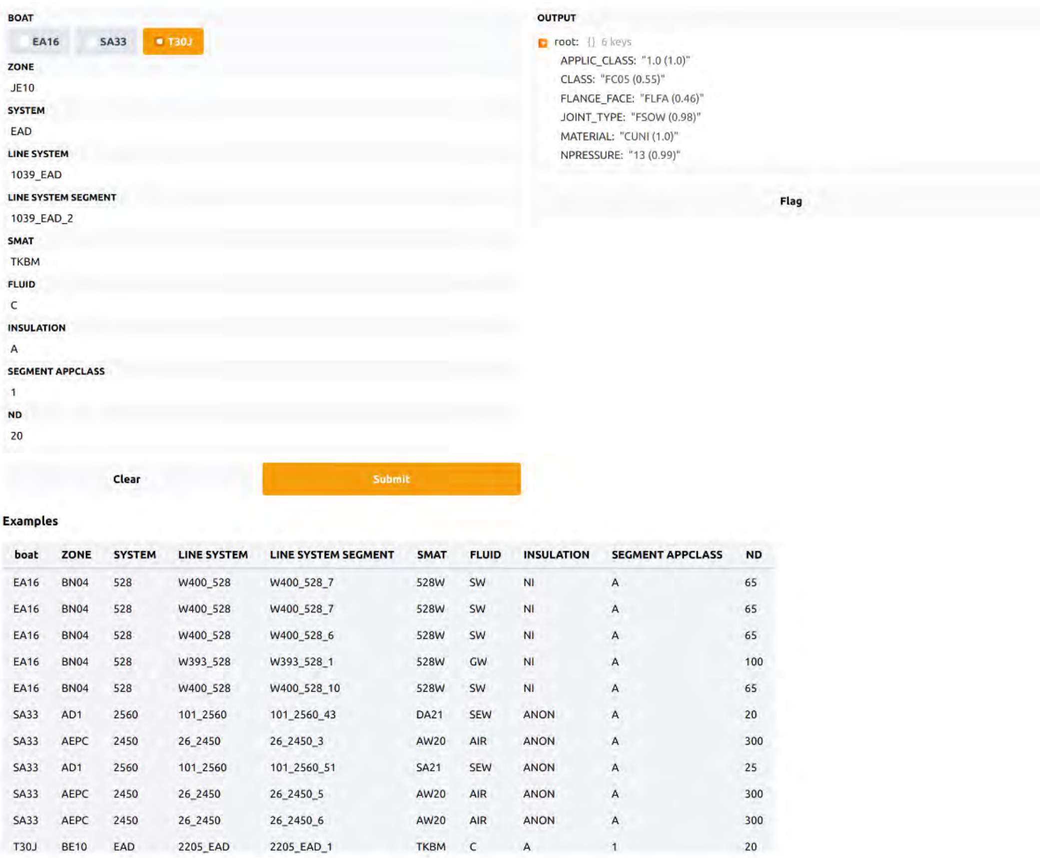

Fig. 8: Analysis of components and values prediction

The idea is to create a model that, assuming the user is going to insert a component in a specific segment, it will predict what component the user is going to select and to automatically fill the values needed, saving design time and minimizing the risk of making mistakes, Fig.7.

The system shall use a machine learning algorithm to select the values more adequate to the ship accordingly to the analysis made on the data that currently exist in the project. These values can also be presented to users for verification, as exposed in Fig.8.

7. Conclusions

AI is one of the enabling technologies of digital transformation that has the greatest potential among those that make up the fourth industrial revolution. Knowing their characteristics and possibilities is essential to decide their application to certain processes and products, especially industrial ones and very particularly those related to the marine sector. It is important to identify the value that AI can contribute to the use cases where it can be applied.

The use of AI in industrial environments such as the marine one is just beginning. There is still a long way to go, in the field of design, optimization of projects, maintenance of data and results.

With or without debate, the truth is that AI is present day by day in our environment, and its development will be growing. However, a part of all the advances that the AI will bring to our sector, we will continue to need intelligent people, people who are smarter than machines and who are ahead of them, because there are capacities of the human being who can never be embedded in an AI.

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No-one in Control: Unmanned Control Rooms for Unmanned Ships?

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Abstract

This concept paper will discuss interaction between humans and Maritime Autonomous Surface Ships (MASS). MASS are highly automated, partly manned, or unmanned, ships. Human shortcomings will pose challenges for the design of the Remote Operation Centres monitoring MASS. These problems are related to automation complexity and automation surprise, human out-of-the-loop syndrome, Black Swan effects and human-automation teaming. In case of total loss of communication, the MASS need to cope without human supervision. In the meantime, the operator in the control centre must be kept in the loop by a digital twin sustaining a simulated reality.

1. Introduction - automation complexity and surprise

Autonomous and remotely operated ships with a varying degree of manning is the in focus of research in many places. The shipping industry seems to be open and interested in this new technology. The ultimate goal might be unmanned navigation with varying promises of cost efficiency and increased safety. The ongoing pandemic with problems relating to international transfer of crews adds to this interest. At the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway, a new 8-year long Centre for Research driven Innovation named "SFI AutoShip" started in 2021 with the aim of supporting the Norwegian industry's attempts to realize autonomous shipping, https://www.ntnu.edu/sfi-autoship. The centre's research will cover four use cases: ocean shipping, short sea shipping, ferries and offshore operations. The project involves several work packages focusing on areas like sensor- and decision-making systems, reliable and secure data infrastructure, models and tools for risk management, cost-effective and environmentally friendly sea transport and fostering of innovation and commercialization. However, as unmanned ships is thought to be remotely supervised the system ultimately involve humans, so Human Factors (HF) and the Remote Operation Centre (ROC) will be the focus of one work package, and this will also be the focus of this paper.

When I first encountered the idea of autonomous commercial ships in 2012 in the MUNIN project, it was first thought of as ridiculous, http://www.unmanned-ship.org/munin/. When presented in 2013 before the IALA ENAV committee many of the members laughed and said, "come back in 25 years". Today, 8 years later, we are already well underway, and the IMO has brought in autonomous ships on its agenda.

2. IMO and the Degrees of autonomy

IMO is currently assessing regulation that might apply to ships with varying degrees of automation. In 2017, following a proposal by a number of member states, IMO's Maritime Safety Committee (MSC) agreed to include the issue of MASS on its agenda, *IMO (2021)*. This would be in the form of a scoping exercise to determine how the safe, secure and environmentally sound operation of MASS may be introduced in IMO instruments. The degrees of autonomy identified for the purpose of the scoping exercise were:

1. Degree one: Ship with automated processes and decision support: Seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control.
2. Degree two: Remotely controlled ship with seafarers on board: The ship is controlled and operated from another location. Seafarers are available on board to take control and to operate the shipboard systems and functions.
3. Degree three: Remotely controlled ship without seafarers on board: The ship is controlled and operated from another location. There are no seafarers on board.

4. Degree four: Fully autonomous ship: The operating system of the ship is able to make decisions and determine actions by itself.

Human Factors in unmanned navigation may seem contradictory, but looking at the IMO's list of degrees of automation where levels 1-3 all contain some kind of human-automation interaction, and level 4 must be understood as that there will be some kind of a remote fallback solution. One may of course imagine a "fire-and-forget" type of MASS, but it would most certainly contain a "call-me-if-you run-into-problems" type of function.

It is therefore clear that Human Factors will play a role for MASS operation. The underlying assumption is that automation and artificial intelligence can only cope to a certain extent, and that there will always be complex situations which has not been considered by the programmers of the automation or that has not been encountered before by the AI, where a human operator will be asked to step in. This is not the place to define the difference between "automated" and "autonomous", but for the sake of this paper, with "automated" I mean "pre-programmed" while "autonomous" include some kind of artificial intelligence capable of learning from its experience and thus solving complex tasks it has not been pre-programmed to do. Further, with "complex" I mean problems with an infinite solution space, as opposed to merely "complicated" problems that has a finite solution space. With time we might see ship systems that will evolve from merely "highly automated" to "autonomous". The more mature the autonomous system is, the more seldom requests for assistance from a remote operator will be, this in turn will distance the operator further and further from the loop.

3. Well-functioning automation

Let's take short look at what well-functioning automation might lead to. The best proxy for a Remote Operation Centre (ROC) that we presently have is the ship bridge (although, on the bridge you only control your own ship, in an ROC it is assumed you may supervise many). Reliable ship automation has been available for a long time. The first self-steering device was first developed within aviation in 1912 by the Sperry Corporation (although Joshua Slocum, the first person to sail solo around the world on his yacht 'Spray' 1895-98, used a contraption with ropes to dynamically lash the wheel when conditions were favourable for self-steering, *Slocum (1899)*. Ever since WWII merchant ships has been fitted with better and better autopilots able to keep a precise course in open waters and in many sea states, thus making the helmsman's role redundant leaving only the watch officer on the bridge during daytime. In the age of electronic navigation the autopilot can be set in "track-following mode", meaning it can automatically following the different courses of a detailed voyage plan, applying rudder with a set turn radius at precise "wheel-over points", also in complicated inshore areas such as the Norwegian Westcoast (personal communication). In these situations, the watch officer can be left with nothing but monitoring functions while the ship is navigating automatically. Such well-functioning automation has lessened the workload on the bridge and could potentially increase the amount of time spent on higher-level navigational tasks such as improving Situation Awareness and planning collision avoidance. However, this is not always the case as we shall see in the following example.

In August 2015 two ships collided on the Scottish coast east of Peterhead. In full daylight, good visibility, and smooth seas the two vessels had slowly, and for several hours, approached each other on almost parallel courses that converged at the place of collision. Both vessels had been on autopilot, both watch offices had been comfortably seated on their respective bridge chairs in such a way that they had their backs towards the other ship. Both ships were visible on their radar and ECDIS screens. But the approaching collision went undetected until bulbous bow of one vessel struck the other midships. One may ask how such an accident is possible? The accident investigation concluded, unsurprisingly, that the two ships "collided because a proper lookout was not being kept on either vessel", *MAIB (2016)*. The UK Maritime Accident Investigation Branch's analysis concludes that "human error" was the cause. With well-functioning automation, in this case autopilots capable of precise course keeping, radar and electronic charts capable of keeping look-out and fix positions, you would imagine that this type of accidents would be impossible. The accident report talks about “complacency and poor watchkeeping practices,” but humans are humans: complacency, distraction and fatigue are part of the human behaviour. (“Complacency” is a human trait that according to the dictionary means: “self-satisfaction especially when accompanied by unawareness of actual dangers or deficiencies”.) This type of accidents could be called “boredom induced”.

If the “navigating navigator” is reduced to merely a “monitoring navigator” the risk is that he or she might not be “present” when needed. This has been studied with cockpit automation in the aviation industry. Precisely as in the maritime domain, automation can relieve pilots of tedious control tasks and afford them more time to think ahead. Paradoxically, automation has also been shown to lead to lesser awareness. A study by *Casner et al. (2015)* from NASA and University of California, Santa Barbara, found that pilots reported a smaller percentage of task-at-hand thoughts (27% vs. 50%) and a greater percentage of higher-level flight-related thoughts (56% vs. 29%) when using the higher level of automation compared to a lower. However, when all was going according to plan, using either levels of automation, pilots also reported a higher percentage of task-unrelated thoughts (21%) than they did when in the midst of an unsuccessful performance (7%). Task-unrelated thoughts peaked at 25%. The authors concluded that, although cockpit automation may provide pilots with more time to think, it may also encourage pilots to reinvest only some of this mental free time in thinking flight-related thoughts.

Already Bainbridge writes in her seminal paper “Ironies of automation” from 1983 that “We know from many 'vigilance" studies, *Mackworth (1950),* that it is impossible for even a highly motivated human being to maintain effective visual attention towards a source of information on which very little happens, for more than about half an hour,” *Bainbridge (1983),* p.776. So, that humans are bad at performing monitoring tasks is nothing new.

4. Black Swans

Events that are thought impossible and comes as a surprise are sometimes called Black Swan events. (Today we can see real Black Swans in Saint James’s park in London, but once they were an example of “impossible creatures”.)

We have all experience of otherwise well-functioning systems that crash and leave us with blue screens, or error messages of different kinds. Remote operations are especially vulnerable, as the passed year of Pandemic remote on-line video-based work has shown us. Even highly safety critical systems, such as airplane automation fails as was demonstrated in a tragic accident in 2009.

In the night of the 1st of June 2009 Air France fight 447 from Rio to Paris, dropped out of the sky in the middle of the Atlantic Ocean. And with it, 228 passengers, *BEA (2012)*. The plane was in mid-air approaching the Inter-Tropical Convergence Zone, the area where air masses coming from the different hemispheres converge at the humid equatorial latitude, with thunderstorms as a result. In the middle of the night the second and third pilot where monitoring the automated systems in the cockpit while the captain was taking a rest. The flight had been uneventful until now as the plane approached a storm cell. Suddenly the automatic flight management system lost its speed input from the triple redundant pitot tubes (which were all clogged by ice) and handed, what had until then been a fully automatic airplane, into the hands of the relatively inexperienced junior pilot flying. The accident investigation tells a story of mismatch between the automation interface and the pilots trying to make sense of what they saw on the screens. The highly automated flight system had encountered a situation it was not programmed to handle. While nothing dramatic had actually happened, apart from the system losing speed input from the three speed sensors, the system decided it could not function anymore and handed the airplane over in fully manual mode to a pilot that was not in the loop, and who did not understand what was happening. The system was not programmed to have a fall-back solution such as “maintain course, speed and altitude and wait for sensor input to come back” – which it did a few seconds later, but then it was too late. The highly automated flight system on AF447 which interfaced the human and the machine through sophisticated computer programs that in this case was difficult to understand and handle correctly. Automation can prevent human mistakes when every-thing works as planned but became incomprehensible for the same operators when computers do not receive proper inputs and go blind, *Faccini (2013)*. This could also happen in a Remote Operation Centre for MASS.

5. The Remote Operations Centre

In the ROC one or several operators will monitor one or many MASS. In the MUNIN project we suggested "six" vessels per operator, based on "active monitoring" where an operator spent 10 minutes every hour "onboard" each MASS to check on some crucial key performance indicators, thus keeping him- or herself in-the-loop, *Porathe et al. (2020)*. However, this will of cause depend on the complexity level of the area where each vessel is presently in. In a complicated harbour approach, the operator might only cope with one ship, while on the open sea, he or she could handle several. But one might also assume that in a well-functioning system "active" monitoring might soon drift into "passive monitoring" where the operator's attention will need to be call by alarms. In a situation where the operator is "unavailable" the MASS would automatically go into a "minimum risk condition", *DNV GL (2018)*. In such a case the problem for the human operator would be to understand what is wrong, and what are my options? We elaborated in *Porathe et al. (2020)* on different "operator reediness levels" to cope with the out-of-the-loop syndrome, *Ensley and Kiris (1995*). Operators would then be assigned an operator readiness level of "in control" or "3 minutes" for ships in constrained waters or port approaches, while and readiness level of "one hour" could be sufficient for monitoring several ships on the ocean.

For the operator in the ROC there are two pitfalls: underload and overload. For a well-functioning, mature autonomous ship system, the former will probably be the greater risk: boredom. Week after week monitoring well-functioning ships. Ship Traffic Management (STM) system will in the future take care of separation between vessels, and make the monitoring task even more boring. The collision outside the Scottish east coast illustrated above serves as an example of such a boredom induced accident.

On the other hand, when something does go wrong and the alarm bells go off, the risk is that we will have a situation of information overload as the operator calls for information needed to get into the loop.

6. Quickly getting into the loop

In the MUNIN project we envisioned a minimum information display where there basically was only a "top flag" that was either green, yellow or red. We envisioned that a reliable automation would handle all situations or else send an alarm. The vision is visualised in Fig.1. Here one vessel has turned on a yellow warning (top right screen), meaning it has detected a stand-on vessel and is now automatically doing a starboard evasive manoeuvre, according to Rule 15 of the COLREGS, visualised as the green AR track on the camera image to the left. However, there will be much more complex situations where the automation will not be able to cope and needs assistance from shore. In such a case, when the operator must quickly get into the loop, the information design needs to be optimized. A "quickly-getting-into-the-loop display" (QGILD) must fulfil the following three objectives:

1) It must give a tactical update to achieve an at-a-glance understanding of the present situation. Maybe pointing to relevant COLREG rules, traffic, wind sea state, daylight or darkness. Showing all necessary information - but not more! (Which is easier said than done.) It could e.g. be an egocentric situation view as illustrated in the left screen in Fig.1.
2) It should offer automation transparency, giving the operator an at-a-glance understanding of how the expert-system sees the situation, and its suggestions for solving it and what it will do if the operator does not respond ("the minimum risk condition"). If it is a collision avoidance situation, it should give track suggestions on a chart, but it could also be about fire onboard, equipment failure, etc.

3) Finally, it must supply tools for intervention, simple and intuitive ways for the operator to intervene and assist or override the automation system, e.g. controllers to handle or action buttons to execute manoeuvres. And all of this must work for “any situation”. (Remember the Black Swans?)

Here we need to develop true human-automation teamwork.

Fig.1: The MUNIN vision, http://www.unmanned-ship.org/munin/: Shore Control Centre interface

7. Human-automation teaming?

“The problem is not over-automation, it is inappropriate feedback and interaction”, *Norman (1990)*. He proposed that the problem was not the presence of automation, but rather its inappropriate design. As an example, he mentions an aircraft accident in 1985 where a China Airlines 747 suffered a slow loss of engine trust on one of its engines. The engine failure caused the plane to yaw to one side, but the autopilot compensated, until it finally reached the limit of its compensatory abilities and could no longer keep the plane stable. The plane then went into a dive that nearly caused it to crash. Norman reasons, that if the plan had been flown by a human first officer who flew the plan by hand, he would not keep compensating without saying a word. He would probably say something like 'I seem to be correcting this thing more and more—I wonder what's happening?' By communicating observations and possible discrepancies each crew member keeps the rest in the loop. And so must the automation.

Norman (1990), p.1, concludes: “The problem, I suggest, is that the automation is at an intermediate level of intelligence, powerful enough to take over control that used to be done by people, but not powerful enough to handle all abnormalities. Moreover, its level of intelligence is insufficient to provide the continual, appropriate feedback that occurs naturally among human operators. This is the source of the current difficulties. To solve this problem, the automation should either be made less intelligent or more so, but the current level is quite inappropriate.” That was in 1990. Are we still at that intermediate level? I would say yes, we are.

Design of the interface between the human operator and the artificial intelligence will be a most important research area for MASS systems. Automation transparency (Explainable AI) and glass-box-information visualisation will be important key words. Experiment HMIs needs to be tested in simulator environments with several bridges run by human navigators against ships navigated by automation/AI and supported by an ROC.

But if or when the automation fails. What if the ROC operator is not there?

8. The unmanned Remote-Control Centre

One common controversy between engineers and Human Factors people when it comes to human-automation interaction is, "how fast should an operator be able to take over in case of an emergency?" Should it be it six seconds or six minutes? Engineers want this hand-over period to be short, so that engineering problems can be covered by the human operator (like it was supposed to in the AF447 accident). The Human Factors side talks about time-to-get-into-the-loop, operators being distracted, or fatigued and not being able to keep vigilant for long periods, like in the NASA study on pilots monitoring automation, referenced above. My view is even more polarized: maybe we cannot rely on that there will be any operator available at all. "All our operators are presently occupied, please hold the line" might be a possible scenario when a MASS calls for help. Or maybe more likely, there is a communication glitch just when the MASS needed help the most. In such situations the autonomous navigation system must always have a fallback solution, it must always know what to do if the human operator is not there. Because "stop and hoover", or "drop anchor", might not always be the right thing to do when connection is lost. What this means is that the MASS must always be prepared to be "fully autonomous" in the extreme sense of the word. This will be valid objections for both Degree 3 and 4 of the IMO scale. For all practical purposes, we must always assume that the ROC could be unmanned.

9. A digital twin of the automation system

Communication glitches between ROC and MASS might be a very probable scenario. The question is what happens then for the remote operator in the ROC? Do all screens turn black, and he or she will be completely in the dark? The communication outage will have led to a situation where the ship must make decision by itself, as outlined in the section above, but when the communication system is up and running again after one or many minutes the operator could be completely out of the loop. Therefore, a suggestion is to keep a copy of the automation/AI system onboard also in the ROC. The copy (or "digital twin") will under normal circumstances be connected to the onboard system so that they are always compatible. Should connection fail, the ROC system will keep feeding the operator with information about what the onboard system will do when it now has lost communication with shore. Camera feed will of course be lost, but some information, e.g. AIS, might be gathered from land-based infrastructure (in Norway from the Coastal Administrations AIS network), and the camera view could be instantly replaced by an egocentric VR view constructed from a digital topographical model and ship models positioned by AIS data from land-based sources. Such a "simulated reality" will of course start to drift off from what really happens in quite a short time, and control commands based on this simulated reality will not pass through to the MASS, but will for some time keep the operator in the loop ready for when the communication is back again.

10. Conclusions

In this paper I have discussed concepts relating to the interaction between a Maritime Autonomous Surface Ship (MASS) and the Remote Operations Centre (ROC). Human Factors issues relating to human-automation interaction will be important to take into consideration when designing the overall MASS system. These issues have to do with information overload and underload (boredom), out-of-the-loop syndrome and human-automation teaming. These and other problems, such as communication outages, might lead to that the remote operation centre might be practically "unmanned" when the MASS calls for help, and must is all cases be able to go gracefully into a fail-to-safe state ("minimum risk conditions). To still keep the operator in the loop during a communication outage, a "digital-twin" of the ship environment should be kept updated at all times in the remote centre.

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3D Model – Technology Island in Ship Design or a Central Piece for Shipbuilding Project Data?

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Abstract

Historically, 3D models have been at the core of ship design solutions in shipbuilding. With the development of IT technology, the 3D model has taken on the position of a 3D dashboard and is more widely used. Adding information on top of the 3D model makes it an information-rich digital twin of the project, which can be used on any device, including AR/VR/XR. Besides the visual role, it can serve as a dashboard for communication, integration, consolidation, and an entry point for different interfaces at any stage of a shipyard's activities. This paper presents several use cases of 3D dashboards based on CADMATIC eShare use by the shipyards and outlines the primary considerations for using digital twin platforms in shipbuilding.

1. Introduction

Shipbuilding has used 3D models for several decades. The contemporary design and building process relies heavily on 3D modeling as an engineering tool; it enables high-quality production data, facilitates project review, eases change management, and more. However, recent interest in digital twins, *Cabos and Rostock (2018)*, and related expectations for digital shipbuilding raise questions about the use of 3D models. What is the potential value of using the same 3D model throughout the whole shipbuilding management process? How can the complexities of the same 3D model be managed for changing purposes throughout the ship's life cycle?

In an ideal world, the 3D model is created incrementally, starting from the concept stage of the shipbuilding project. It is enhanced with details and used to extract production data; it may serve as a basis for marketing materials and rendered visualization, including AR/VR/XR and contain converted or raw 3D laser-scanned data. The same 3D model or a or filtered model can be used later for maintenance, repair, operation, training and retrofit purposes. It can become a digital twin that lives its digital life alongside the actual vessel.

The focus of shipbuilding design solutions on the 3D model might be too narrow: the 3D model is a "technology island" similar to an "automation island" in the production process. Many technological advancements focus on creating 3D models – from basic design to detailed design and production. Each stage of the shipbuilding process often focuses only on its own outcomes, such as hull design or piping and outfitting, and related outputs. Typically, only neighboring disciplines and project stages are covered, leaving gaps or ignoring the overall strategy and integration of the digital thread. For example, a model created for basic design and class approval is often not used for detailed design purposes. Plate nesting information is linked with planning and production but lacks alignment with outfitting disciplines. Material management needs to align EBOM and MBOM without verifying the latest changes in the design model. There are many other similar examples.

While each gap can be addressed individually, the overall PLM approach is still novel for shipbuilding. The expectation is that PLM can potentially resolve most of these inconsistencies. However, a typical PLM solution originates from mechanical CAD models with significantly fewer parts and less complexity. It only brings the automated approach of splitting the 3D model into parts and managing information about each piece independently. This approach considers a 3D model as a composition of many small 3D models for every item, and it can be enhanced by using 3D as a unifying interface to access data of each specific part. This article explores the typical uses of the 3D model in the shipbuilding cycle from the concept and contract stages to operation. It outlines specific use cases and explores the future possibilities of using 3D models in shipbuilding management.

2. 3D model and shipbuilding management activities

It is a relatively novel approach to use the 3D model throughout the entire shipbuilding process. It is a commonly used and accepted way of designing highly complex ships. The use of 2D drawings has become increasingly outdated, and the order of creation has turned to the extraction of 2D drawings from 3D models, and not 3D modeling according to 2D documentation. This was not the case some 15 years ago, when 2D drawings were the basis of ship design, approval, and production. In recent years, there have been significant shifts that were enabled by new computing technology and comprehensive access to 3D manipulation. It has provided numerous possibilities to avoid 2D documents. Examples of these include direct interfaces with CNC machines, welding robots and cobots, new options to submit 3D models for class approvals, and more.

All these uses of the 3D model are different. In some cases, the 3D model comes as an engineering model, and the visual representation only visualizes calculated data, such as in the case of 3D fairing or surface definition. In the case of 3D detailed design, it manages the arrangement complexities in crowded 3D spaces. It allows users to resolve conflicts in 3D arrangement, select the correct materials, and provides a common place for all disciplines to connect – align equipment with foundations, electrical cables with motor connections, etc.

Software providers embed an extremely high level of knowledge in modern CAD software and 3D modeling. CAD applications harness numerous automated functions, engineering practices, standards, and knowledge that have been accumulated over decades in the shipbuilding industry, *Filius (2020)*. As a result, in the final stages of 3D modeling, a complete model is available that includes all disciplines, accurate geometrical information, topological and parametrical connections, a significant amount of meta-data, and links with 2D outputs for change management. At this stage, the focus of attention often shifts from design to production, assembly, and construction, and the 3D model remains an extra item or attachment to the project documentation package.

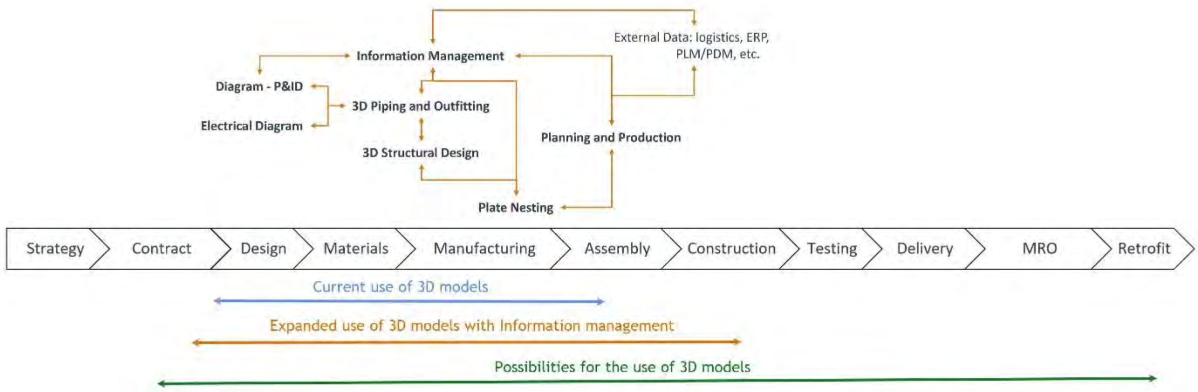

Fig.1: 3D model use in shipbuilding timeline – current, extended, and possible

Fig.1 illustrates the typical use of the 3D model in CAD against the timeline of the overall shipbuilding management process. The period of 3D model use is somewhat restricted to design and partially includes construction. Typically, it is limited and fragmented. For example, it is possible to have several 3D models for different purposes or several models that were created in different design software packages. Specialized tools for calculations may have been used or several subcontractors responsible for only a limited part of the design may also have been involved. Interoperability between software solutions could facilitate the conversion and merging of 3D models into one entity, but it might become an obstacle if formats are not compatible. This issue has been tackled extensively in recent years with efforts to create standardized forms, such as IGES, JT, or STEP, and with project-based conversions as described by *Sieranski and Zerbst (2019)*.

3. Example use cases of 3D models at shipyards

Several 3D model use case examples are presented in Fig.2, based on experience accumulated by CADMATIC in everyday interactions with shipyards and ship design offices. The examples illustrate the extended use of 3D models and do not include obvious scenarios, such as using the 3D model for collaboration design or production information purposes. The use cases are divided into three main clusters: Boost for communication, Integration of information flows, and Platform for Digital Twin.

Fig.2: Main use case scenarios for extended use of 3D models in shipbuilding.

3.1. Boost for communication

3.1.1 Communication within shipyards and shipyard networks

The use of 3D models facilitates communication within shipyards, and between the shipyard and subcontractors and shipyard groups. Instead of a paper- or email-based information flow, the engineering office and shipyard can use 3D model mark-ups and interfaces to VR/AR/XR applications. 3D models, which often include 3D laser-scanned data, are a more realistic representation of the ship than 2D documentation, project structures, or data tables.

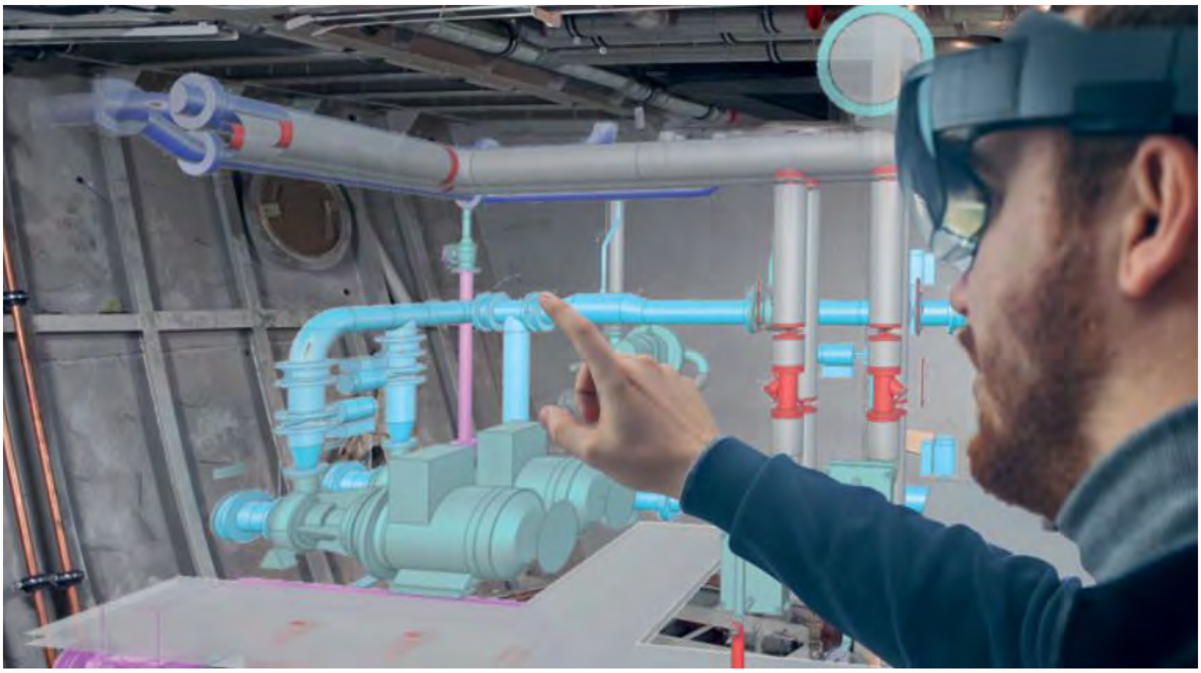

Fig.3: Example of using a 3D model in CADMATIC eShare for MS HoloLens at a production site

It was long accepted that the lack of IT technology prevented effective manipulation of 3D models due to heavy GPU requirements and the lack of VR developments, *Agis et al. (2020)*. However, these constraints are in the past; current technologies enable 3D visualization on powerful workstations and tablets and XR devices, such as VR headsets or MS Hololens, with the possibility to manipulate 3D models in mixed reality and align 3D models with real objects. In recent years, much progress has been made in the use of 3D models in almost every ship design stage and beyond. A general conclusion is that the use of 3D models significantly enhances communication for all parties involved and serves as a more natural means of communication than old-fashioned 2D drawings and data sheets. Understanding a work breakdown structure based on a list of components or installation schedules is challenging. The same task is greatly eased when it can be visualized with colors inside the 3D model and interacted with in a live setting.

3.1.2 Project review and handover

Traditionally, shipbuilding CAD 3D models were locked inside ship design packages, required skills to navigate, and were otherwise available only for designers or for project review at most. However, with mature IT supporting a large amount of 3D data in recent years, it became possible to provide ship models for inspection on demand. In addition, it became possible to liberate 3D shipbuilding data and use significantly lighter and cheaper devices than specialized CAD desktops or virtual reality caves. 3D models in VR have been used for shipowner review, design validation, and production support.

The 3D model can remain as an extra item in the package that contains project information, including documentation, data from production and construction, and all related notes. These packages of information data about the same project will be different for the use of design collaboration, class approval, shipyard production workshops or shipowner. Alternatively, it can effectively serve as a natural entry point for information searches and to open linked data stored in other systems.

3.1.3 Visualization of installation instructions and replacement of paper drawings

Manufacturing and installation instructions can be visualized on mobile or wearable devices, thereby replacing paper drawings in the approval and production stage. Furthermore, direct data from the 3D model, such as geometrical representation, metadata, BOM, and workshop information is provided online to installation teams on site. At the same time, the outfitting part installation status can be added for progress following and as feedback to the design team.

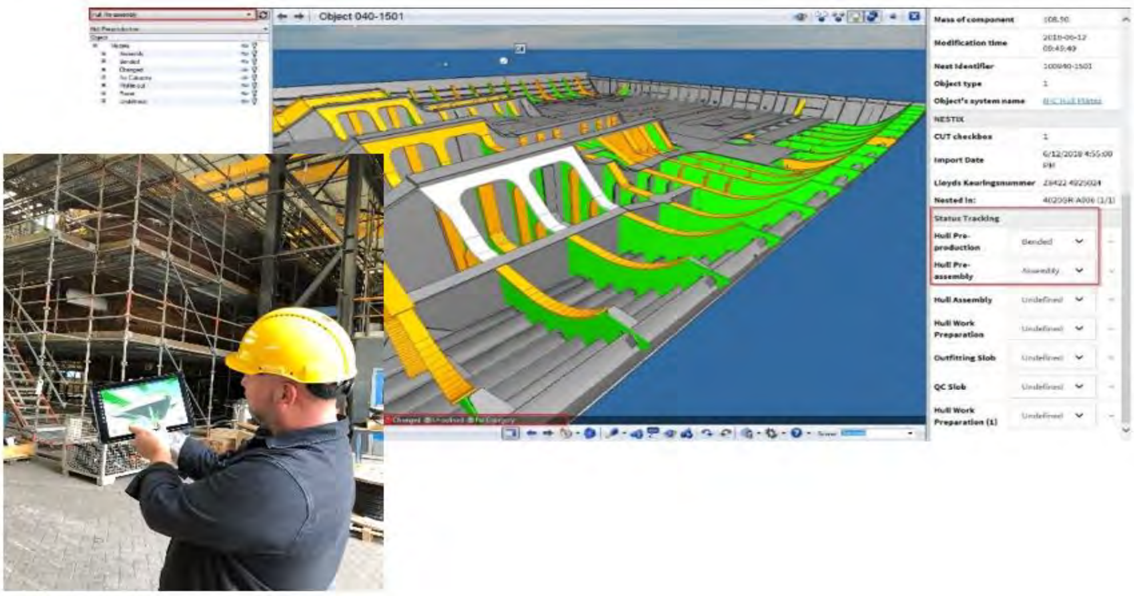

Fig.4: Example of using a 3D model in the CADMATIC eShare platform at a production site.

Interaction with 3D data distinctively differentiates the digital era – the first attempts to standardize drawings aimed to improve readability and production quality. For the data-native generation, this poses unnatural limitations. Instead of a static snapshot, people prefer to obtain data on demand and then manipulate it. They also use the 3D model as an easy-to-understand interface, *Seppälä (2019).*

3.2. Integration of information flows

3.2.1 Integration with ERP, PLM/PDM, planning systems, and Manufacturing Execution System (MES)

For 3D evaluation, monitoring progress, and checking the parts and materials, shipyards can integrate the 3D model with PLM/PDM or ERP systems. Linked documents and system parts, including dimensional drawings and piping parts, provide a rich context when they are efficiently visualized as separate parts and as an integral part of the vessels' 3D model. In addition, a 3D model linked to task planning at the detailed work breakdown level, kitting packages, and BOM visualizes planning, retrieval of tasks (welding, grinding, painting), and resource planning.

Integrating the 3D model with planning and manufacturing execution systems helps visualize the scheduling status of parts and blocks with color-coding, adding a visual aspect to work scheduling and progress monitoring. It also provides context for each work task by relating it to the overall production process and background data. Resource management systems are often focused on narrow tasks and reporting processes, leaving workshop staff without a direct link to the product they are producing and a significant amount of design and production-generated information, *Seppälä and Brink (2020)*.

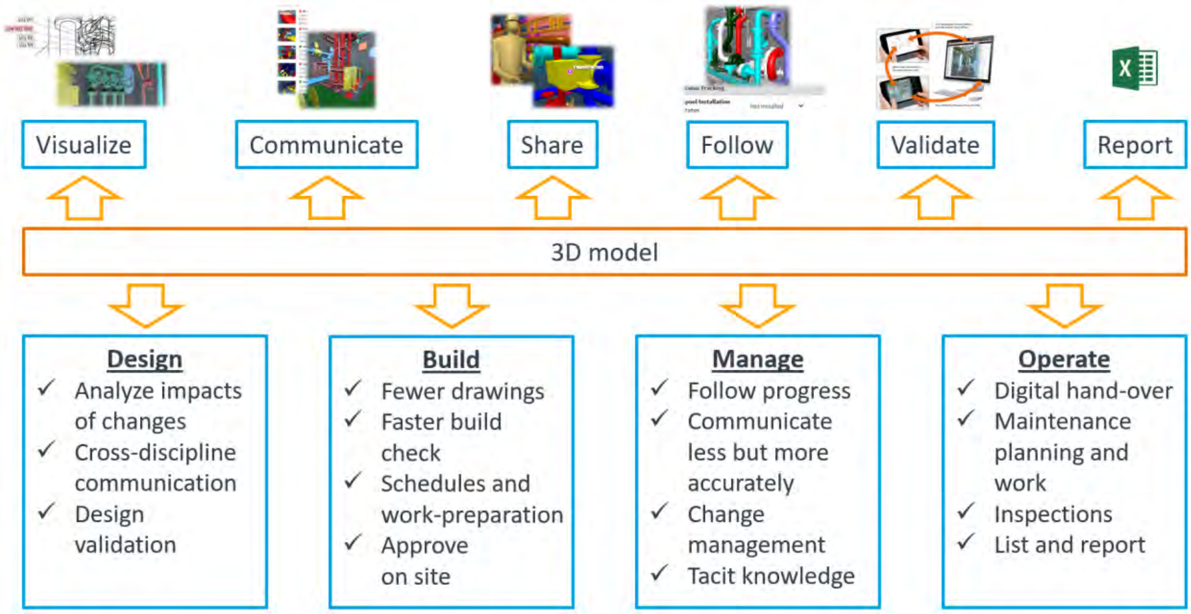

Fig.5: Typical scenarios for using information in the primary shipbuilding process - from design to operation

3.2.2 Integration with work packages and component tracking

Linking materials, fittings, and equipment with their digital counterparts in a 3D model provides additional benefits for integration. For work preparation and planning, the 3D model can be integrated with work planning systems and ERP for work package kitting visualization and shipyard resource management. Any item can be found in the digital model using RFID or QR codes as well as all related data from integrated systems – attributes, drawings, and instructions accessed on site. The shipyard can benefit from integrating 3D models with production systems, such as nesting and assembly controls. The hull production statuses for cutting, bending/pre-assembly, approval, and section assembly are visualized and monitored using a 3D model on a suitable device.

3.3. Platform for Digital Twin

Consolidating shipbuilding management information on a 3D dashboard and using the 3D model as a natural interface have considerable potential in shipbuilding. The discussion about the advantages and uses of the 3D model has, on the one hand, been an ongoing debate over the last decade, and on the other hand, – has provided a new perspective on continuity in the shipbuilding process and the blurring of borders between design stages and even disciplines.

Traditionally, ship design software has stored data that originated in the design stages and extended slightly towards the production stage. Decades ago, 3D browsers aimed to fill this gap, at least partially, by providing the possibility to review 3D models outside CAD. This approach was expanded recently with information management systems that serve as a platform for consolidating 3D data and for providing smart functionality to access data needed for different stages and purposes. The primary use cases of this access were presented in the previous sections. However, one question needs special attention – how to store and access all the data that comprises the digital twin If one considers this question purely from a PLM perspective, the answer will be as simple as storing any 3D models, such as the basic design model, detailed design model, production model with geometrical data for each object, etc., alongside other documentation drawings, schedules etc. APDM system would provide a secure vault for 3D model storage, which would diminish the use of 3D data. Alternatively, using a shipbuilding-specific information management platform and supporting incremental creation of the 3D model and its use would boost digital shipbuilding.

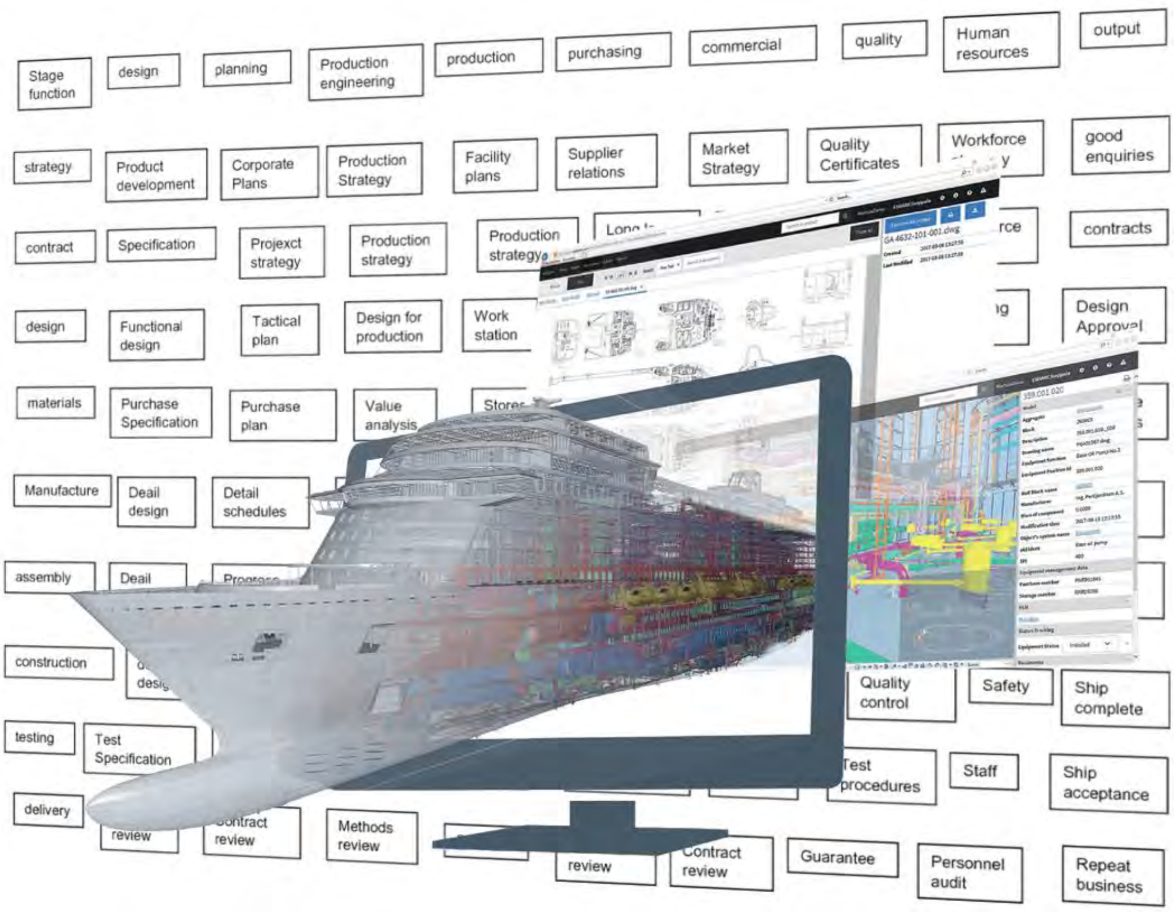

Fig.6: Shipbuilding activity map: stages of activities vs. functions and 3D model use, adapted from *Bruce (2021)*

Combining several 3D models and converting 3D models between different formats help to facilitate a one-model approach. It helps to consolidate 3D data in one platform and supports the approach based on a "universal" digital twin, in contrast with a specialized digital model for each use case.

4. Summary

The single source of truth is an attractive analogy and a trap at the same time. It provides the illusion of a central access point for all up-to-date data. The contemporary reality at shipyards is far from the ideal situation with a myriad of specialized systems, interfaces, and data storage methods used in different departments. A step that would provide unification is the expansion of the use of the 3D model, thereby ensuring support for specific needs of each discipline and shipbuilding process stage.

The use of 3D models would boost communication and integration without compromising shipbuilding's specific purposes. Hopefully, in the future, 3D models will become a landscape instead of an island, and 3D technology will support the shipbuilding cycle as a whole, not as segmented stages.

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Design Patterns for Intelligent Services Based on Digital Twins

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Abstract

In this paper we extend the portfolio of digital twin patterns by introducing a set of service patterns. Each of the patterns supplies a reference architecture and a design template for specific digital services that provide operational intelligence and decision support based on a digital twin. The identified patterns are a virtual sensor, context sensor, fingerprint, anomaly, root cause, scout, and mirror. The patterns are catalogued according to their description, minimum requirements, added value and possible limitations along with conceptual diagram of how the pattern might be realized by coupling digital twin "building blocks".

1. Introduction

For human beings, patterns are a crucial tool for conceptualizing objects, experiences, ideas and sensory input. Patterns capture shared features across a set of phenomena and organize these features into a structure that can be used to match later observations and provide a recipe for implementation. In the context of this paper, patterns provide a means for generalizing disparate digital twin solutions across different domains into a catalogue.

The concept of patterns in design and architecture is commonly attributed to Christopher Alexander who says, "Each pattern describes a problem which occurs over and over again in our environment and then describes the core of the solution to that problem in such a way that you can use the solution a million times over, without doing it the same way twice", *Gamma et al. (1994)*

The interest in design patterns received a boost through the book published by *Gamma et al. (1994).* They identified a set of 23 core patterns applied in software systems development. These patterns captured the underlying architectural and algorithmic solution to a specific problem independent of programming language and application area, thus providing a common reference for the whole software development community. The digital twin patterns described in this paper are inspired by their work.

Gamma et al. organized their design patterns according to their intended purpose - creational, structural and behavioural. This was the inspiration for a previous paper at COMPIT, *Erikstad (2018)*. Here, a set of patterns were described that captured the identity, state, and behaviour of a real asset, such as a ship, a semisubmersible, an offshore wind turbine or a fish farm, is captured in a virtual model in close to real time. These patterns described reusable solution templates applicable to different classes of marine systems design and operation problems, combining core digital model building blocks, such as onboard sensor observations of loads or responses, physics-based analysis components, as well as data stream analytics. This included a baseline pattern for a DT driven by sensor observation on the real asset, a load-based pattern where the DT behaviour was predicted from observations of external loads, a benchmark pattern for detecting deviations between observed and expected behaviour, and the ML proxy pattern where physics-based prediction of behaviour was replaced by a continuous learning algorithm. Application cases of these patterns were further extended by the paper by *Drazen et al. (2019)* at COMPIT 2019, applying the benchmark twin pattern for a shipboard engine and a baseline twin for ship fatigue damage.

We consider the DTs built on these structural patterns not as an end in itself. Rather, they are important means for supporting digital services that provide value through improved insight and decision support, see *Erikstad (2019)*. In the same way as for other engineering systems, they should be designed towards meeting the well-defined needs of identified stakeholders. These services can be classified according to their decision level and temporal perspective, as illustrated in Fig.2.

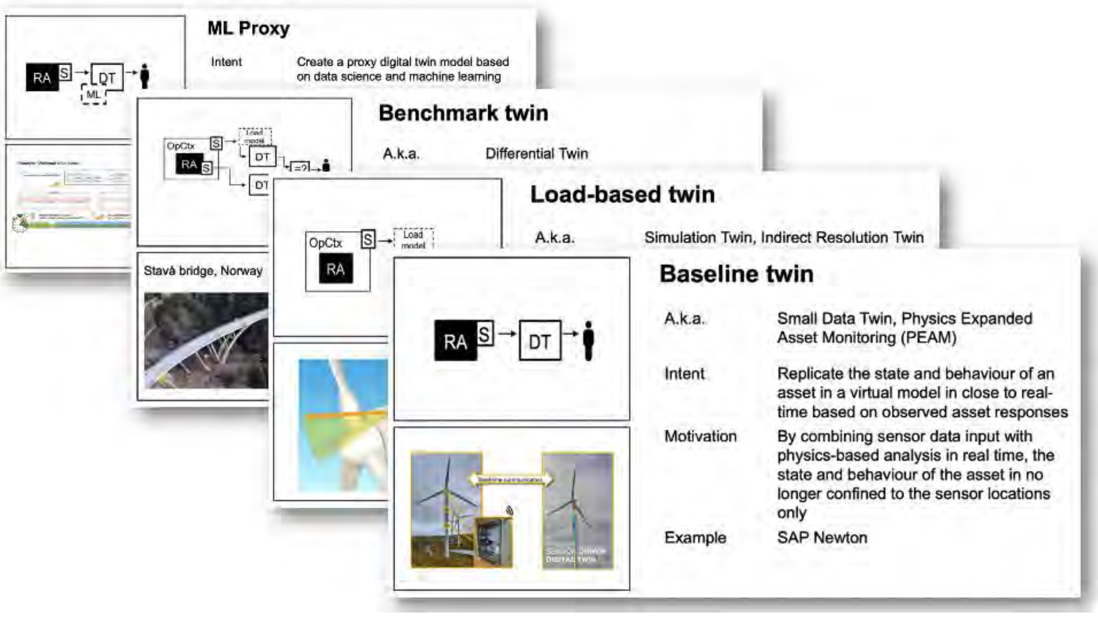

Fig.1: Examples of structural patterns from *Erikstad (2018)*

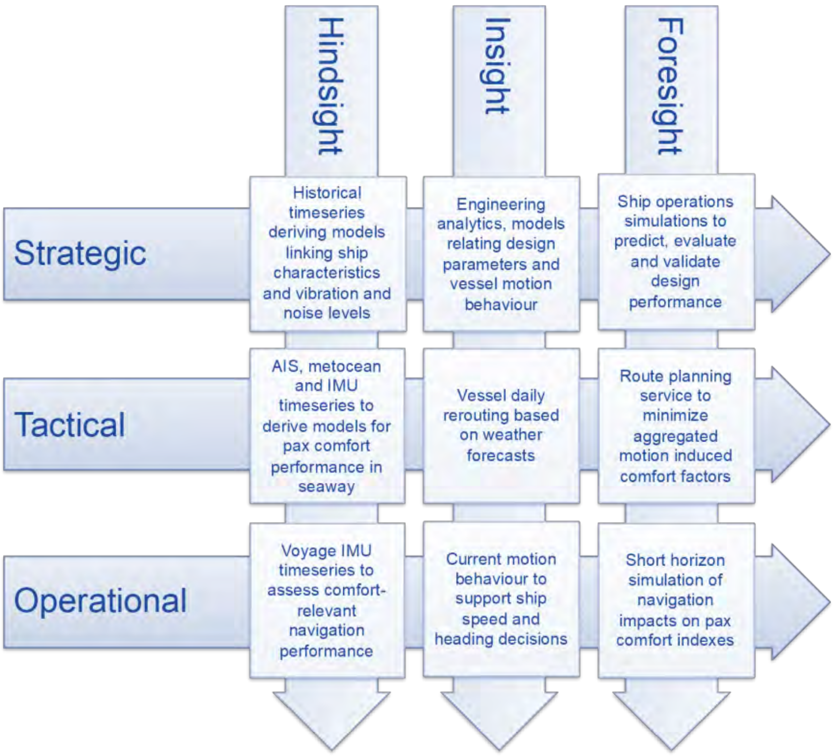

Fig.2: Classifying digital services according to their decision level and temporal perspective, using a pax comfort service as an example

Naturally, digital services based on digital twins come in many forms towards a large range of applications. Still, if we start to analyze across various implementations, there are certain solution patterns that are common across the set. We have named these service patterns.

2. What is a service pattern, and why is it useful?

We define a DT-based <u>service</u> pattern as "a common, high level, conceptual solution for realizing (partly or fully) a digital service, based on a DT that delivers value to stakeholders by decision support and/or improved insight related the asset's state or operational behaviour".

This division between the role of the DT itself, which is to provide the means, and the service to exploit the opportunities exposed by the DT, is central. This follows the proposition of *Minerva et al. (2020)* which offers a consolidated digital twin definition in which they aim to transcend context. Service patterns focus on the value adding property, servitization of digital twins.

Servitization potentiates a lifelong link between enterprise, its product, and users. Prominently, the appeal of products can be increased through new in-service functions and customer interactions, *Minerva et al. (2020)*. Traditionally, prognostic health management of assets have been hampered by uncertainty in the material behaviour, operational conditions and loads that the products face in deploymen, *Uhlenkamp et al. (2019)*. This new coupling between operational data and virtual models enables a means through which uncertainties in asset health management (material behaviour, operational context, and loads) can be reduced through appropriate digital services.

3. Generic service patterns using digital twins

Our suggested service patterns propose generic digital twin configurations which could be repeatedly applied in versatile contexts towards service value. Eight patterns have been identified, Table I.

Table I: A list of identified service patterns for digital twins

	Name	Value provided by service
	Virtual sensor	Provide insight into asset behaviour on locations without sensor observations
	Context sensor	Provide insight into loads and operational context by inverse inference on asset behaviour
	Fingerprint	Understand asset operations by matching against a catalogue of behavioural patterns
	Anomaly	Early detection of faults and critical conditions by comparing observed and predicted behaviour
	Root cause	Identify root cause of observed deviations by reverse engineering physics-based simulations
	Scout	Obtain situational awareness by fast forwarding current operations using simulations and predictive statistics
	Life counter	Aggregate miniscule incremental loads to better exploit actual life capacity and avoid failures
	Mirror	Recreate complete immersive operators experience to manage remote assets

In keeping with the approach of *Gamma et al. (1994)*, the digital twin service patterns are subsequently described using a template including the pattern name, description, minimum requirements, potential benefits, and limitations. Finally, a diagram is offered with each pattern to explain our envisioned configuration of the digital twin building blocks. A table, explaining the graphical elements, is presented in the Appendix, Table A.I.

Erikstad (2019) eluded that digital service may vary in quality and that their design should be subject to cost-benefit analysis as with any product. A Digital Services Maturity Model was proposed based on the level of insight the service was required to deliver, which in turn, is associated with the required model complexity and associated cost. The minimum maturity level will be specified along with each pattern according to the depiction in Fig.3.

Level	1	2	3	4	5
Digital Services Maturity Model [4]	Observe	Measure	Model	Predict	Decide

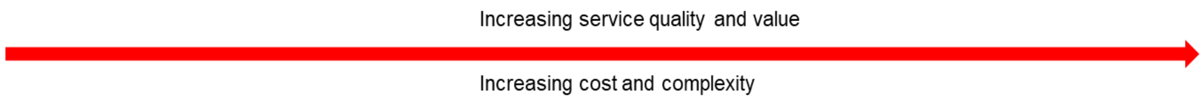

Fig.3: Maturity levels for digital services

A final word of note pertains to the entanglement attribute of digital twins which refers to the linkage between the real asset its virtual representation. *Minerva et al. (2020)* classify entanglement in terms of the connectivity (direct or indirect), promptness (rate of information exchange) and association (uni- or bi-directional). Here, we propose the service patterns with the minimum entanglement required to fulfill the purpose of the service.

4. Service patterns for digital twins

4.1 Virtual sensor

Description: The virtual sensor pattern infers a sensor feed from a digital model at a location where physical sensor placement is absent on the real asset.

What is needed as a minimum?

- A physical asset equipped with sensors to provide a real-time observation of the response of the real asset.
- A digital model from which a virtual response can be determined at the required location. This digital representation could be physics-based (Example: In cases where the location of critical stress should be identified) or data-driven (where corresponding responses have been trained through historical data).
- The maturity level of the DT must be at level 2 (Measure).

Benefit of use: In practice physical sensor placement could be limited by cost, access, practical difficulties, or hazardous environments. If a physics-based model is used in the digital twin, multiple virtual sensor feeds could be obtained through investment in a subset of real sensors.

Possible limitations: The virtual sensor feed is not necessarily the true response of the asset. In fact, the virtual feed would be inaccurate in cases where physics-based models fail to represent the actual situation. In the case of data-driven models situations could arise which lie outside of the original training data.

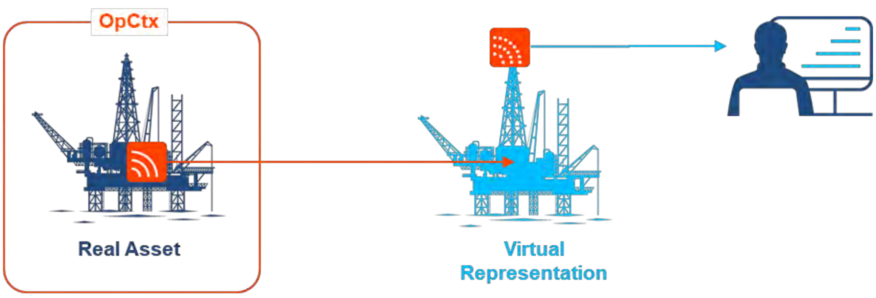

Fig.4: The virtual sensor pattern

4.2 Context sensor

Description: A context sensor provides insight into loads and operational context by inverse inferences from asset response measurements.

What is needed as a minimum?

- Sensor feed(s) from the physical asset to relay the asset behaviour.
- A digital model that receives the sensor feed from the asset and solves an inverse problem to determine the operational context / load.
- The level of the DT must be at level 3 (Model)

Benefit of use: This DT pattern can be used to determine the loads to which an asset is exposed where direct load measurements are not possible / not cost-effective / hazardous.

Possible limitations: Indirect force determination entails the solution of inverse models which are prone to instability and can be time-consuming to solve.

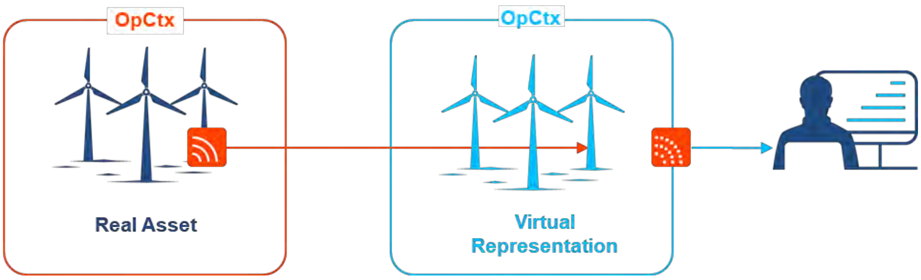

Fig.5: The context sensor pattern

4.3 Fingerprint

Description: The fingerprint recognizes the operational response of a real asset by matching it to a catalogue of pre-generated behavioural patterns which were generated using a digital model.

What is needed as a minimum?

- A physics-based model through which catalogue states can be induced to extract virtual response patterns for the catalogue of fingerprints.
- A sensor is required to measure the response on the real asset.
- An algorithm to match the real-time sensor feed to the catalogue responses.
- The level of the DT must be at level 3 (Model)

Benefit of use: This pattern could be used to pre-empt failure in assets, especially where failures are catastrophic or expensive. Virtualized sensor feeds can be generated for early stage failure scenarios without requiring that the system should physically have operated in this response mode before (example: Worn raceway of a wind turbine bearing).

Possible limitations: Noisy measurements from real responses can deviate from the fingerprints in the catalogue. This could hamper the detection of catalogue states in operation.

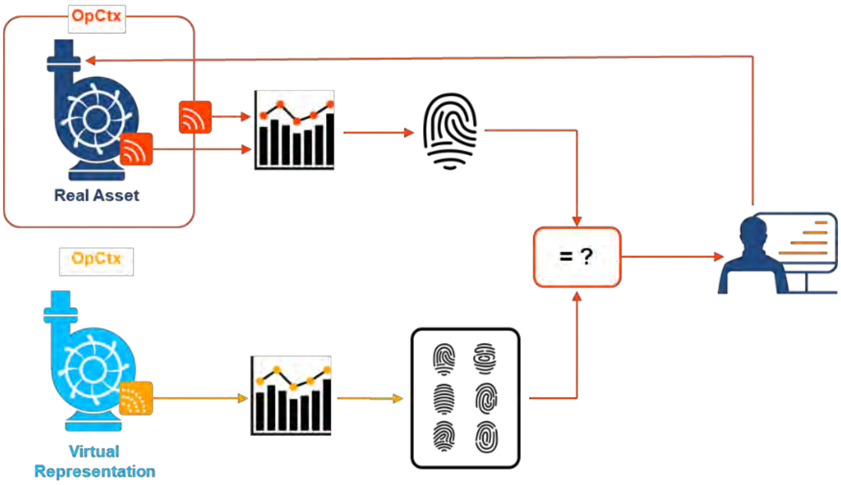

Fig.6: The fingerprint pattern

4.4 Anomaly

Description: The anomaly pattern detects abnormal behaviour of the asset when sensor responses from the real asset deviate from expected responses from a virtual model which is exposed to the same context or load.

What is needed as a minimum?

- A sensor feed which supplies the operational context of the real asset to the digital model as input.
- A digital model that generates a virtual sensor feed with the expected asset response.
- A second sensor feed, containing the asset response which can be compared with the virtual sensor feed.
- The level of the DT must be at level 3 (Model)

Benefit of use: The anomaly pattern has the dual benefit of informing the user on the expected performance of the asset. This pattern can function effectively using data-driven models based on historical data without requiring domain-specific expertise to detect changes in the asset performance.

Possible limitations: Sensible anomaly detection will require thresholding to specify how much the operational response may vary from the digitally generated response before and anomaly is detected.

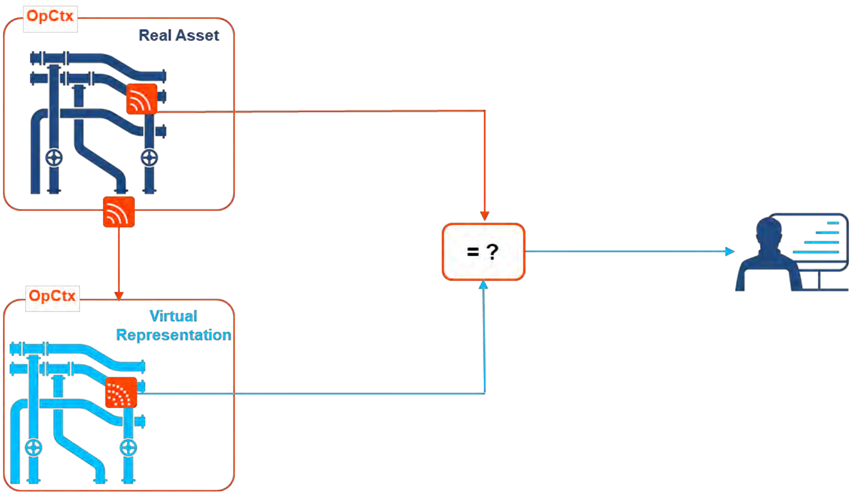

Fig.7: The anomaly pattern

4.5 Root cause

Description: The root cause pattern determines the reason for asset response deviations by reverse engineering physics-based simulations.

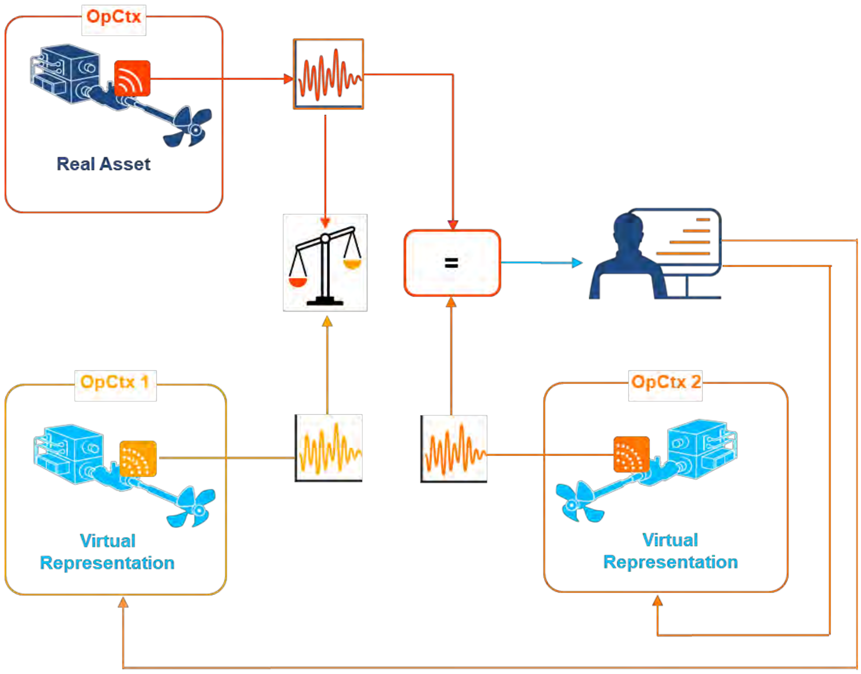

Fig.8: The root cause pattern

What is needed as a minimum?

- Sufficient sensors to provide a real-time observation of the actual asset behaviour and operational context.
- A physics-based model through which possible causes / contexts can be introduced virtually
- Sufficient entanglement to establish if the virtually induced root cause matches the deviating response of the real asset.
- The level of the DT must be at level 3 (Model)

Possible limitations: Sufficient digital representation is required to realize the value of the root cause pattern. The successful identification of the root cause will rely on the causal inputs the model receives. (Example: Pump cavitation which arises because of changes in system piping cannot be identified if the piping is not included in the model).

4.6 Scout

Description: The scout contributes situational awareness by fast forwarding current operations using simulations and predictive statistics.

What is needed as a minimum?

- Sufficient sensors to provide a real-time observation of the actual asset behaviour and operational context.
- A virtual model through which likely asset responses can be simulated because of different operational decisions or contexts.
- The level of the DT must be at level 4 (Predict)

Benefits of use: Users of an asset can make optimal decisions during deployment based on information from a scout.

Possible limitations: Predictions based on data-driven models may fail if the "what-if" scenario falls outside of the fitted data. The predictive nature of the model and the strong entanglement required increases the level of sophistication of the model and therewith the associated cost.

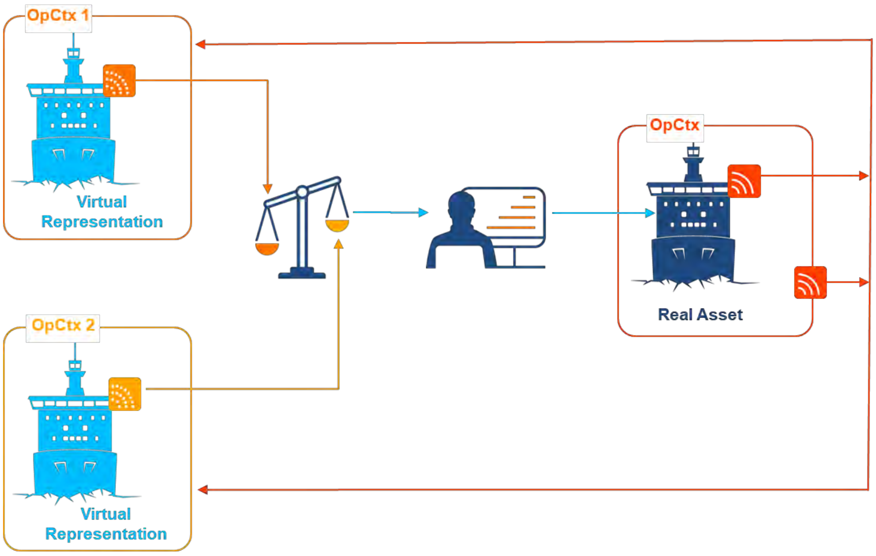

Fig.9: The scout pattern

4.7 Life counter

Description: The life counter aggregates actually-incurred stress cycles to exploit asset life capacity and avoid failures.

What is needed as a minimum?

- Sufficient sensors to provide real-time observations of the actual asset behaviour.
- A virtual model to determine the operational life expenditure from sensor measurements.
- The level of the DT must be at level 4 (Predict) to estimate remaining useful life.

Benefit of use: Uncertainties in prognostic health management can be reduced by including the actual built-geometry, material behaviour, operational conditions, and operational loads into remaining-useful-life calculations. A physics-based model adds the additional benefit of virtual sensors so that the location with the most critical stress concentration can be determined – not limited to the measurement location on the asset.

Possible limitations: The life counter should capture all factors which my encroach on service life such as structural detail, corrosive behaviour, maintenance interventions (such as cracks repaired by welds). The accurate inclusion of inspection data – manual or automated is key to leverage model benefits.

Example: *VanDerHorn and Mahadevan (2021)* document the use of a lifecounter to optimize the operational availability and expenses over the life of a naval vessel.

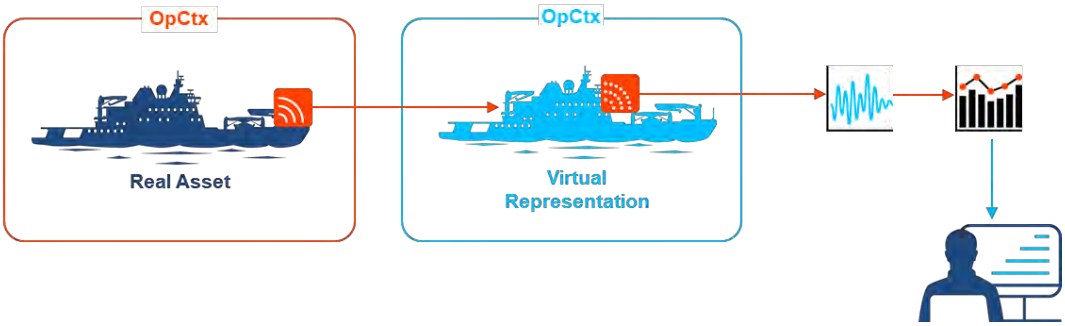

Fig.10: The life counter pattern

4.8 Mirror

Description: A mirror creates an immersive operators' experience to manage remote / inaccessible assets.

What is needed as a minimum?

- Sufficient sensors to provide real-time observations of the actual asset behaviour.
- A virtual model to represent the state and behaviour of the asset into the user in real-time.
- User-to-asset entanglement through which the digital model can act as the controlling instance.

Benefit of use: A mirror allows a more immersive and informed user experience by using model capabilities such as augmented reality, visualization or information displays to communicate the state and behaviour of a real asset. The ability of the user to prompt real asset, allows for adjustments in deployment and business potentials such as integrated customer support and field service.

Possible limitations: Fully-entangled user control could require the inclusion of expansive contextual modelling to ensure safe remote operation of the asset. The increased complexity of the mirror digital twin will imply an increase in the associated cost.

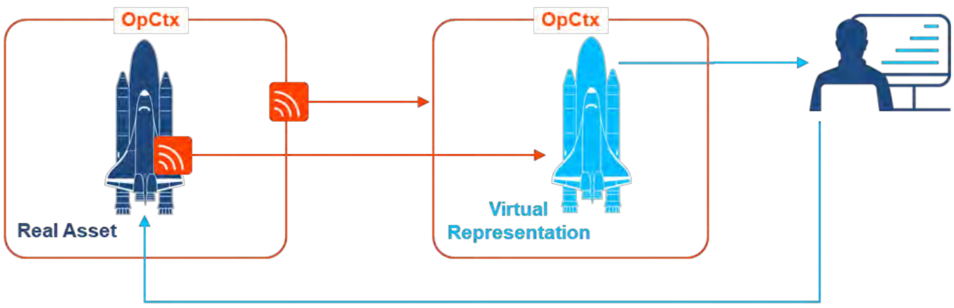

Fig.11: The mirror pattern

5. Conclusion

In this paper we have proposed eight service patterns for digital twins. A digital twin based service pattern captures a common, high level, conceptual solution for realizing a digital service, based on a digital twin that delivers value to stakeholders by decision support and/or improved insight related the asset's state or operational behaviour. The service patterns are named according to their intended purpose and include virtual and context sensors, fingerprint, anomaly, root cause, scout, life counter and mirror patterns.

The proposed patterns focus on solutions templates to unhinge the servitization value of digital twins. This attribute adds value through the connection between enterprise, its product, and users where the harnessing of operational sensor data and virtual models enable new in-service functions and customer interactions. Importantly, digital twin functionality enables the calibration of operational performance of assets against expected behaviour. This leverages new potentials to inform and optimize asset management.

We believe that identifying and describing solution patterns are an important contribution to a new research field. Such patterns captures common characteristics and structures across domains and application areas, thus supporting a wider research community. Further, patterns contribute to the establishment of shared concepts and vocabularies. Related to digital twins, we think the focus will shift from focusing on the realization of the digital twin itself, towards how we can exploit the insight provided by the digital twin towards developing digital services that provides value through improved decision making.

Acknowledgement

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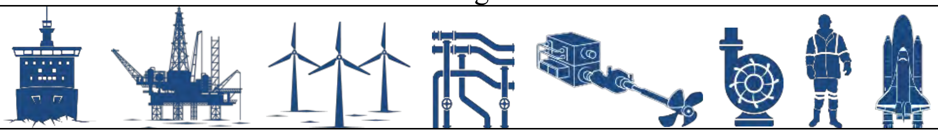
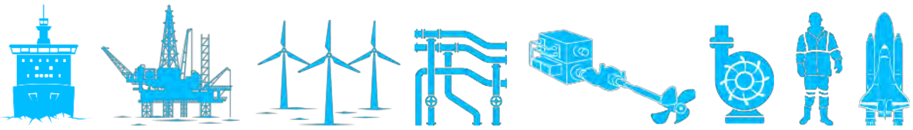
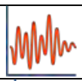
Appendix

Table A.I: A list of DT building blocks & icons

Real asset / Physical object	
Digital representation / Logical object	
Sensor	
Virtual sensor	
Operational context	
Data	
Analysis / Processing	
Comparison	
Pattern	
Pattern catalogue	
User	

A Convolutional Neural Network Developed to Predict Speed Using Operational Data

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Abstract

In the shipping industry power prediction methods are commonly used. An option is to predict the power based with a theoretical analysis. However, with a purely theoretical approach it is not possible to evaluate all operating conditions. The second, simulation methods, are able to describe all the necessary quantities in detail. Nonetheless, simulation requires relatively high computational power. Thus, the current power prediction methods used in the shipping industry are insufficiently all-encompassing or accessible. Therefore, a machine learning approach is developed to calculate the ships speed over ground using neural network and convolutional neural network techniques. For training and validation of the model operational data from a fall-pipe vessel is used. The developed method combined with ship motion could result in an optimal power usage, and thus leads to reduced fuel consumption and emissions. The method could also be used for optimised routing. Although in this case study applied to one single vessel, the developed model is generally applicable, providing ship management companies the possibility to train the model with operational data from their fleet, therewith, offering the possibility of reduced fuel consumption and thus emissions on a global level.

1. Introduction

In the shipping industry power prediction methods are commonly used. Current speed prediction methods are limited and/or expensive. A machine learning approach can improve the accuracy and decrease the cost of speed and resistance predictions, *Brandsæter and Vanem (2018)*, *Liang et al. (2019), Petersen et al. (2012), Pedersen and Larsen (2009)*. No such speed prediction model is available tailored to the shipping industry as a whole. In order to predict the ships speed and resistance, this research presents an improved power prediction method, based on operational data. This method should be able to:

- accurately predict speed and resistance of a vessel,
- for different operational conditions,
- that is easy to use and widely accessible (on board) (low computational power).

1.1 Literature Review

Based on the requirements, the need arises for a method that predicts speed and resistance of a vessel for different operational conditions that is widely accessible. Thus, a literature review is presented about, the current speed and resistance calculation methods in shipping, their mutual benefits and shortcomings and other relevant machine learning applications in the field of marine engineering.

There are several methods presented in literature and currently applied in industry. *Petersen et al. (2012)* suggests dividing the different methods in four separate groups, namely:

1. Standardised traditional methods relying mostly on describing the hull using typical parameters, *Holtrop and Mennen (1982), Holtrop (1984)*
2. Direct model testing in towing tanks, *Chuang and Steen (2011)*
3. Methods based on computational fluid dynamics, *Sadat-Hosseini et al. (2013), Ozdemir and Barlas (2017)*

4. Regression methods that use sensor measurement data, *Brandsæter and Vanem (2018), Petersen et al. (2012)*

These methods differ in their dependence on either theoretical base using physical laws, or empirical and data driven insights that base their descriptions on statistics of historical data. In the following sections the methods are described and evaluated in more detail.

1.1.1 Traditional Methods

A widely used approximate power prediction method was introduced by *Holtrop and Mennen (1982)* and later improved in *Holtrop (1984). Nikolopoulos and Boulougouris (2019)* states that Holtrop-Mennen is considered to be one of the most accurate and computational efficient methods for estimation and speed prediction. The method uses equations that describe various resistance components that add up to a total resistance from which, together with the propulsion power the engine and screws, provide the speed can predicted.

The equations presented in *Holtrop (1984)*, are based on a regression analysis of the data of 334 ship models. The ship hulls were parameterized in a range of dimension ratios. With these equations, using the parameters of the hull ratios as input, resistance and speed can be predicted for a vessel.

Another method that is used to predict resistance and speed of a vessel is presented in *Hollenbach et al. (1999). Matulja and Dejhalla (2007)* states that this method is at least as precise as other traditional methods. The Hollenbach method is based on the data of 433 ships and these ships are from the era between 1980 and 1995. These more recent hulls are more similar to the hulls designed nowadays compared to methods based on older hull shapes. *Feijo and De Oliveira (2020)* conclude that the mean prediction scenario of Hollenbach and the prediction scenario of Holtrop-Mennen are very similar, and no preference is given. The method proposed in *Hollenbach et al. (1999)* does give a maximum and a minimum which can be useful for different operating conditions.

Traditional methods are reasonably accurate at predicting speed and resistance. *Matulja and Dejhalla (2007), Nikolopoulos and Boulougouris (2019), Grabowska and Szczuko (2015)* all agree that Holtrop-Mennen gives a good estimate of the ship's speed and resistance. *Matulja and Dejhalla (2007), Grabowska and Szczuko (2015)* conclude that Hollenbach is also able to make accurate predictions. Another benefit of both methods is, the calculations are based on dimensions of the hull, which are determined in the earlier design phase. Therefore, these traditional methods can be applied early in the design process.

However, Holtrop-Mennen as well as Hollenbach can only accurately predict speed and resistance, if the dimensions of the hull are in between the boundaries of the method. Therefore, not for all ships predictions can be made. Also as explained by *Bertram (2012)*, these methods are outdated and underestimate the resistance of modern hulls. Furthermore, the traditional methods do not take environmental factors into account. According to *Mao et al. (2016)* environmental factors can increase ship resistance by more than 50-100%.

1.1.2 Towing Tank Direct Model Testing

These methods are based on the design of downsized ship models that are tested in towing tanks. In the research presented in *Chuang and Steen (2011)*, a scale model of a 8000 DWT tanker is used and is towed through a large towing tank (L/W/D= 260/10/5). In the research presented in *Chuang and Steen (2011)* waves were created in the towing tank to measure the influence these waves had on the speed of the ship. The force needed to tow the vessel model through the towing tank is recorded. From these measurements the resistance and speed of the real size vessel are be predicted.

Direct model tests are performed in a controlled environment, all influential factors can be tested separately, *Chuang and Steen (2011)*. However, for direct model testing a towing tank is required. Towing tanks are expensive and testing approximately costs around 10000 dollars per test, *Barczak (2020)*. Furthermore, in model test the waves brake different from the full-scale ship, resulting in scale effects, leading to a slight accuracy problem *Bertram (2014)*.

1.1.3 Computational Fluid Dynamics (CFD) Methods

Prediction methods based on CFD simulate the flow around the hull of the ship. Most CFD methods roughly take the following steps:

- Preprocessing:
  - Forming the geometry and physical bounds of the problem, to extract fluid domain and volume
  - Discretization of the fluid domain and volume
  - Defining the physical modelling, e.g. conservation laws and equations of fluid motion
  - Definition of the boundary conditions. E.g. the fluid behaviour, initial system conditions, reciprocally interaction between fluid and objects and properties of bounding surfaces
- Simulation: iterative solving the equation for each discretization step
- Processing the outcome, visually as well as analytically

Sadat-Hosseini et al. (2013) verified this technique for added resistance for the KVLCC2 ship model in short and long waves. *Ozdemir and Barlas (2017)* also tested added resistance for the KVLCC2 that was created by waves. The KVLCC2 is a ship model that is based on the design of the KVLCC model. The KVLCC model was presented in *Van et al. (2000)* to verify CFD models with the measuring of flow experimental and comparing it to the flow calculated by the CFD algorithm. This made the verification of CFD models possible and thereby confirming the model. The KVLCC2 model is presented in *Hino (2005)* and is a slight differentiation on the hull presented in *Van et al. (2000). Ozdemir and Barlas (2017)* concludes that the CFD model can calculate the total resistance with a margin of 4.1 % of the experimental value. Another conclusion of *Ozdemir and Barlas (2017)* is that since the hull profile is very complex, the motion, and thus resistance, behaves highly nonlinearly. This is a useful insight for the choice of models regarding the developed method.

With CFD models every hull type can be tested and the outcome is able to illustrate which part of the hull generates most resistance, *Sadat-Hosseini et al. (2013)*. Earlier CFD methods were based on elementary flow models, resulting in less precise results, compared to enhanced CFD models *Bertram (2014)*. However, CFD calculations are expensive and time consuming, *Cui et al. (2012), Gatin (2019).*

1.1.4 Regression Methods

Regression methods rely on the statistical interference of historical data, *Brandsæter and Vanem (2018). In Petersen et al. (2012)* two different techniques are used to predict the speed of a vessel, Artificial Neural Networks (ANN) and Gaussian Processes (GP). It is concluded that the ANN works better than the GP. *Petersen et al. (2012)* also concludes that a direct comparison with similar work, *Pedersen and Larsen (2009)*, is hard, as different data is used.

Mao et al. (2016) propose and compare a linear model, an autocorrelation method and an autoregressive model. It is concluded that linear regression, without environmental factors, gives poor results. When environmental factors are included, an autoregressive process reduces the prediction errors significantly. Also, *Mao et al. (2016)* stresses that travelling direction has an influence on the speed-resistance relation. Therefore, *Mao et al. (2016)* suggests to only include travelling direction as input value, when there is a clear leading wind and wave direction.

Brandsæter and Vanem (2018) tests various models on their ability to accurately predict ship speed. Based on data regarding ship motions, wind speed relative to the ship and draft. Other external factors are, at least partially, causal to the ship motion and thus accounted for in the data. Hence, this data is not used as input. *Brandsæter and Vanem (2018)* compare a linear regression model (LRM), a general additive model (GAM) and a projection pursuit model (PPR) with a baseline model. For these methods the shaft thrust, wind and sea conditions are used as explanatory variables. *Brandsæter and Vanem (2018)* concludes that in many cases, especially in calm water conditions, the baseline model performs well in terms of prediction accuracy. Furthermore, according to *Brandsæter and Vanem (2018)* more advanced models do not perform better than the baseline model, when only thrust is taken as explanatory variable. However, when environmental factors are taken as explanatory variables the accuracy increased dramatically. This is a valuable insight for this research, as this data is available and thus it is likely to increase the accuracy of the developed model.

Liang et al. (2019) proposes multiple regression models to predict ship speed, based on automatic identification system (AIS) sensor data and known weather data. The weather data is derived from the AIS data, as the position of the ship is known. *Liang et al. (2019)* concludes that linear regression methods do not predict accurately, due to the highly non-linear tendency of speed over ground. Other methods proposed to predict vessel speed based on data, are decision tree regressor and multiple ensemble methods. The ensemble methods used are a random forest regressor, an extra tree regressor and a gradient boost regressor. *Liang et al. (2019)* concludes that the extra tree regressor and random forest regressor are the best for this task.

Kim et al. (2020) use a support vector regression and harvests good results with this method. *Li et al. (2014)* uses varying machine learning techniques and finds that in some situations they perform just as good as RANS solvers, which are a type of CFD method.

For the use and development of regression methods no knowledge of the physical phenomena is required. The underlying mathematical equations do not have to be known to make accurate predictions. Furthermore, all influential phenomena can be taken into account and when the method is implemented it calculates outcomes very fast. However, data is needed the develop the model and regression algorithms rely heavily on the quantity of data. Also, this data needs to be pre-processed, which often is a time-consuming task. Lastly, the training of some methods, for instance convolutional neural networks, can be quite computational heavy.

1.1.5 Other Machine Learning Applications

Over recent years numerous applications of machine learning algorithms have been researched, that are not in the direct field of resistance-speed prediction. This research can provide useful insights, about what approaches are likely to work and which approaches are more likely to fail.

Abramowski (2013) develops a neural network to successfully predict the effective power for a ship. The research presented in *Abramowski (2008)* shows that neural networks are also able to predict ship manoeuvrability. *Abramowski and Zmuda (2008)* develops a method of presenting a hull in parameters using neural networks.

Liang et al. (2019) compare multiple machine learning and traditional algorithms to predict the vessel propulsion power. Concluding, that the machine learning techniques performed significantly better on ships were a lot of data was available, also they observed big drop in performance when little data was available.

1.2 Problem Definition

In the shipping industry power prediction methods are commonly used. As elaborated upon, the statistical design formulas are for a narrow operational range, across many ships, *Holtrop and Mennen (1982), Holtrop (1984), Bertram (2012)*. While simulations are for one case, but initial condition only.

CFD will be more accurate and far more expensive, *Cuiet al. (2012), Gatin (2019), Bertram (2014)*. Concluding, the current speed prediction methods are limited or expensive.

A machine learning approach can improve the accuracy and decrease the cost of speed and resistance predictions, *Brandsæter and Vanem (2018), Liang et al. (2019), Petersen et al. (2012), Pedersen and Larsen (2009)*. No such speed prediction model is available tailored to shipping. In principle, this is a statistical method, based on data from one ship, across many operational conditions, for the as-is, as-built condition. When the quantity of data is large enough with sufficient variation (in speed, draft, trim), results should be equally accurate as simulations at much lower expense.

2. Method

2.1 Scope

This research covers the development of a machine learning algorithm based on the data of one fall pipe ship. The data set consist of approximately 15000 data points. The outcome model of this research is in principle applicable to data from this ship specifically. There is a possibility that the model is also applicable to ships with comparable designs, however this will not be investigated in this research. By nature of machine learning techniques, the accuracy of the predictions of situations that are not in the original data cannot be determined. However, this does not imply that predictions of these situations are not accurate. Rather, it follows that these situations are not within the scope.

2.2 Algorithm Description

2.2.1 Linear Regression

Linear regression models have been used in different parts of science, from psychology to economics. Linear regression is used to model linear relationships between a response variable and explanatory variable(s). The model can be described using the following formula:

$$\hat{y}_i = a_0 + a_1 x_{1i} + a_2 x_{2i} + \cdots + a_m x_{mi} \tag{1}$$

$\hat{y}_i$ the predicted value, x_i the value that is known and used to predict $\hat{y}_i$ and a_i the linear coefficient that states how much a change in x_i influences $\hat{y}_i$.

2.2.2 Artificial Neural Network

The concept of neural networks was first described in *McCulloch and Pitts (1943)*. In *Hebb (1949)* it was proposed that these networks could be trained using a mechanism known as neuroplasticity. The ability of neural networks to be trained by recognition. Current day neural networks are based around the idea of the perceptron, presented first by *Rosenblatt (1958)*. *Aggarwal (2018)* states that perceptrons are able to classify linear data points in the same way as least squares methods. With the difference that perceptrons guarantee to find complete separation, on the condition that the underlying data is linearly separable. Fig.1 shows the conceptual model of a perceptron. X_{ij} with $i \, \varepsilon \, 1,2, \dots, n$ and $j \, \varepsilon \, 1,2, \dots, m$ are the input signals, w_{ij} with $i \, \varepsilon \, 1,2, \dots, n$ and $j \, \varepsilon \, 1,2, \dots, m$ the weights which the inputs are multiplied by before summing in the neuron, φ the activation function, and o_j the output. n represents the number of input signals and *m* the number of alike networks.

Outcome values of a perceptron are calculated using a two-step process. First, the product of weights and input is taken as described in Eq.(3). After this the sum is taken of all these inputs and the output of the sum is fed into the activation function. This transforms the input to output $\hat{y}$ as can be seen in Eq.(2). In the perceptron described by *Rosenblatt (1958)* this activation φ was the step function described in Eq.(4). *Rosenblatt (1958)* stated that this design of the perceptron imitated the working of neurons in animal brains. From Eq.(4), it is evident that the neuron activates, if and only if, the product sum of the inputs and weights is bigger or equal than the critical, qj in 1, in this case 0, value.

$$z = \sum_{i=1}^{n} x_i \, w_i \tag{2}$$

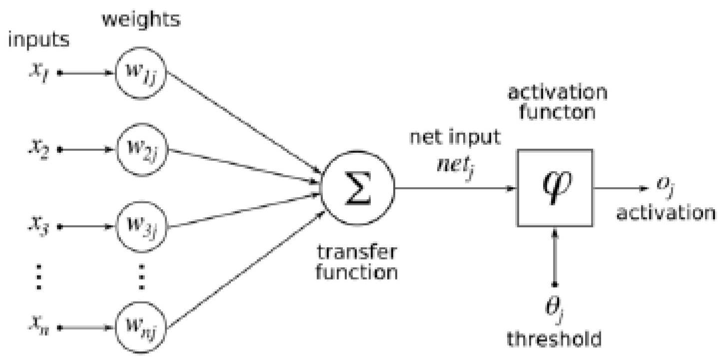

Fig.1: Perceptron model, https://nl.wikipedia.org/wiki/Perceptron

$$\hat{y} = \varphi(z) \tag{3}$$

$$\varphi(z) = \begin{cases} 0 \; if \; z \; < 0 \\ 1 \; if \; z \; \geq 0 \end{cases} \tag{4}$$

While, as illustrated by *Aggarwal (2018)*, the perceptron model guarantees linear separable decision boundaries. Due to its architecture the perceptron model is not able to model nonlinear data, *Minsky and Papert (2017)*. This can be solved when coupling multiple perceptrons together. This way, activation functions can be used, and thus nonlinear boundaries and relations can be mapped.

To map even more complicated relations slightly more complicated models are needed. These models have an input layer, one or more fully connected hidden layers and an output layer. A schematic overview of this model is given in Fig.2. The model presented in Fig.2 can be extended unlimited, keeping the accuracy computation time ratio in eyesight, by varying the number of hidden layers and the size of these hidden layers. The last model that is described is the beginning of the neural networks that are used nowadays. Here the main components are described.

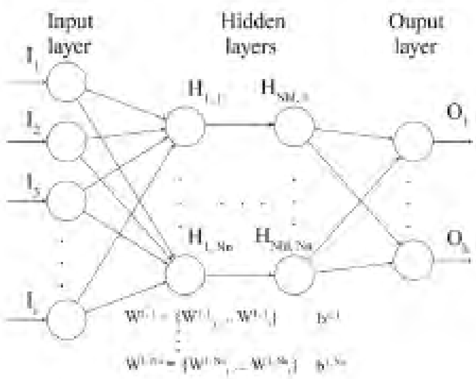

Fig.2: General neural network, [https://www.researchgate.net/figure/General-neural-network architecture-used-in-this-study-33-43-44-The-input-layer fig1_341200069](https://www.researchgate.net/figure/General-neural-network-architecture-used-in-this-study-33-43-44-The-input-layer_fig1_341200069)

Artificial neural networks consist of three components. Neurons, weights and forward propagation. Neurons are the intersection of the network. They have input(s) and a single output that can be send to multiple other neurons. In the neuron the weighted sum of the inputs is taken as described in Eq.(2) and this sum is either directly send as output or put in into an activation function and passed on as output. Weights connect neurons to each other and determine how ’heavy’ the output of the sending neuron should weigh as input of next neuron. At the initiation of the network the weights can either be set at a fixed value equal for all weights, or assigned randomly. Forward propagation (FP) is the process that calculates the output of a neural network. The mathematical process follows the same principles as described in Eqs.(2) and(3).

As shown in the Perceptron model, Fig.1, neurons in layers can apply activation functions to their input to generate their output. Where the Perceptron model use the step function, neural networks are capable of using a whole lot of other activation functions. Activation function can vary between different layers but in the vast majority all neurons in the same layer apply the same activation function. The choice of activation functions is mostly dependent on the type of relationship of the underlying data and the form of the outcome variable. For example, to map a value that can be everything to a probability the Sigmoid function can be used. By using non-linear activation functions the network can be trained to understand nonlinear relations between input and output variables *Leshno and Schocken (1991)*. Before the Rectifier Linear Unit (ReLU), *Rumelhart et al. (1986)*, the sigmoid function was the most widely used activation function, *Pedamonti (2018)*. Functions that are like the Sigmoid function, like the Hyperbolic Tangent (TanH) are also commonly applied. *Pattanayak (2017)* states that because the ReLU functions is faster in training, it has overtaken Sigmoid and the other activation in usage. Another benefit of the ReLU is that, unlike the Sigmoid and TanH, it is not subject to vanishing gradients *Pattanayak (2017)*.

2.2.3 Convolutional Neural Network

Convolutional neural networks have proven to be very useful in various fields of science, from image recognition *Sharma et al. (2018)*, to regression analysis for mass-spectrometry analysis, *Visin et al. (2015)*. The foundation of the idea of modern CNNs lies in the LeNet introduced by *LeCun et al. (1989)*. LeNet stands for LeNet-5, a simple convolutional neural network. LeNet-5 was one of the first convolutional neural networks and promoted the development of deep learning. The original purpose of LeNet was to identify handwritten numbers. Nowadays CNNs are still mainly used for image recognition tasks but also in other applications as audio recognition CNNs are applied. One of the great benefits of CNNs, is that CNNs don’t take single input vectors but take the surrounding data into account. It is clear that this will aid the research, since it’s evident that data in near past is more likely to have a predictive value to speed at this point than data that has a bigger distance on the timeline. Another key benefit of CNNs, is that they are able to share weights across layers which can significantly reduce the number of parameters that the model needs. This makes it possible for CNNs to model very complex structures with limited amounts of parameters. Another benefit is that dimensional information can be stored in the network.

Just like ANNs, CNNs are built of multiple layers. The main part where CNN layers differ from ANN is the dimensional structure that is preserved. Where ANNs mainly use fully connected layers (FCL), where each neuron of layer $l - 1$ is connected to all neurons in layer l, CNNs use a great variety of layer types. All layers have different function which can vary from mapping multidimensional to flattening the outputs of these layers. These flattening layers are mainly used in the final layers of CNNs to map the multidimensional output to a single output vector in a regression problem. If the architecture of a CNNs into considerations one can see that the input of CNNs can thus be, but does not necessarily has to be, of matrix form. Because whole matrices are very big and thus hard to handle a solution was found to still be able to handle matrices as input. Three commonly used sorts of CNN layers are described in the rest of this paragraph.

The convolutional layer is the main component of interest of CNN. The concept of convolutions follows from the assumption that data points share more information with data points that are directly surrounding them than data points that are further away. Since it is computational heavy to calculate with whole matrices. Sub-matrices of the convolutional layer are multiplied with a so-called filter to send this information from layer l to layer $l+1$ *Gulli and Pal (2017)*. By applying the same filter over all the different sub-matrices the convolution is calculated. Also, this way the amount of weights is reduced, since very large input vectors can be mapped as a smaller number of sub-matrices. There are a couple of hyperparameters that define how and which filters are applied to the matrices and what the outputs dimension will be. These hyperparameters and their meaning are:

- Filter size *(F)*: The dimension size of the filters that will be used. Width, Height and if applicable more dimensional measures
- Number of filter (N_f): The number of applied filters
- Stride *(S)*: The size of shift on the axis that is shifted on. For example, a stride of 1 means that the centre of the sub matrix shifts one step on the axis that is iterated
- Padding *(P)*: Padding increases the matrix size with a border width and height of i with zeroes. Padding can be used to preserve matrix input size after the convolution is applied

These parameters are shown in Fig.3. (N_f) is not shown but can be seen as the number of green filters there are in the convolutional layer or layers.

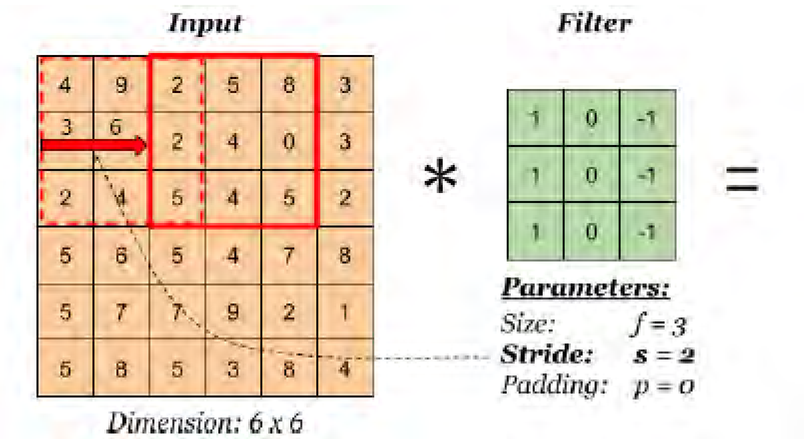

Fig.3: Parameters of CNN, https://stackoverflow.com/questions/51930312/how-to-include-a-custom-filter-in-a-keras-based-cnn

Pooling layers are used to gain dimension reduction (e.g. decrease required memory), by performing an operation on a sub-sample. This way the spatial volume of a matrix can be reduced with huge matrix operations. Max pooling, where the element with the maximum value in a sub matrix is returned, is one of the most common used forms of pooling layers. Other pooling techniques are normalisation pooling and average pooling, *Brownlee (2019)*. Pooling is a robust way of downsizing matrix sizes, *Brownlee (2019). Desphande (2016)* states that there are arguments to remove pooling layers from CNN since the gains that are made by matrix size reduction are nullified by the extra computational costs of the operation performed by the pooling layer. The hyperparameters used by pooling layers are mainly the same as with convolution layers with the important note that with padding the addition of extra zeroes or other numbers problems can occur with minimum and maximum pooling.

A flattening pooling layer is used to transform the matrix representation into a one-dimensional array. For instance, in the last step of image recognition to map to a single word. A flattening layer is a FCL that thus maps all the matrix inputs to a one-dimensional vector. It is important to note that this layer generates a lot of weights, because it is fully connected to all the matrix elements which can be very much.

2.3 Training of ANNs and CNNs

Once the framework is complete, the network is trained. There is a specific training routine that works for ANNs and CNNs. This process is described in this paragraph. In this training process a couple factors are important to know, these so called hyperparameters are described. Furthermore, there is supervised learning, unsupervised learning and reinforcement learning among others. Supervised learning is specifically appropriate for problems where the form of the input data is known and the form of the required output is known, therefore supervised learning is applied in this research.

2.3.1 Backward Propagation

The concept of Backward Propagation (BP) is first described in *Werbos and John (1974)*. Later the method was made available for practical use by *Rumelhart et al. (1986).* The main goal of BP is to describe derivative of the loss function with regards to the weights using an efficient numerical iterative approach. When accomplished other methods can use this information to update the weights of network to lower the loss function value. Since the loss function often is a very difficult function, and thus is not easy to solve analytically the backward propagation method a combination of analytically derived partial derivatives and numerical approaches. A common problem with numerical iterative approaches is that they do no guarantee to find a global minimum, because the method might get stuck in a local minimum. The BP method thus calculate the derivative of the loss function with regard to the weights, to allow other algorithms to use this information to update the weights accordingly. The notation for neural network components is as follows:

- L the amount of layers
- N_l amount of neurons in layer l
- m_{ln} is the output of neuron n in layer l
- $w_{(l+1)j}^{l(i)}$ is the weight from node *i* in layer l to node j in layer l + 1 and w_{ln} denotes all weights into node *n* in layer l
- m_{0n} is input n
- $m_{(L+1)n}$ is the output of the neural network
- z_{lm} is the sum product of all the inputs from layer l - 1 to node m in layer l

The starting point of the algorithm is to calculate the derivative of the loss function notated as E. After this the weights from layer L+1 are updated, after this the weights of layer L are updated and so on until layer 1 is reached. Important to note is that the formulations will first be described on the level of the nodes. The matrix notation will be derived from this representation per node. Since the goal is to minimise the loss function while updating the weights it is important to express the derivative of loss in terms of the weights and their derivatives. To accomplish this also the derivative of the loss function in terms of m_{ln} and z_l are needed, because these are needed to propagate either forward or backward through the network. Using BP the error function and it's derivative are described. This is used to update the weights to train a better network. Following, hyper parameters are described that play a crucial role in updating of the weights.

2.3.2 Hyper Parameter Tuning

Weights are not the only parameters present in neural networks. There are numerous, so called, hyper parameters that are of influence to the networks behaviour and training process. The number of layers and number of neurons or filters are also hyper parameters. The most commonly used hyper parameters are:

- Learning rate (η): How heavily should the weights be updated after each iteration
- Batch size: How much time point should be put in per iteration
- Specific optimiser parameters: some optimiser algorithms have specific hyper parameters

3. Experimental Setup

This paragraph describes the experimental setup, which is used to train, test and verify the models. Also methods that can speed up training and prevent overfitting are described. These experiments are conducted to create the most accurate possible model for this data set and compare the results.

3.1 System Specifics

The models in this research are implemented using Python (version 3.8). The packages that are used for the model implementations are SKlearn, Keras, Tensorflow and Pytorch. The experiments are all conducted on a laptop running on Mac OS catalina with a 3 GHz i7 processor and 8 GB RAM storage. When considering computation times, these factors have to be taken into account.

3.2 Model Implementation

3.2.1 Data Preparation

For linear regression no data preparation needed is required. For the ANNs and CNNs the input data is normalised. This can improve predictions and reduce computation time *Sola and Sevilla (1997).* Normalisation can also prevent fading gradients with certain activation function such as the sigmoid function. With normalisation the data is scaled to certain characteristics of the data set. For instance, with min-max scaling all data is scaled between 0 and 1 or -1 and 1 with the max value of the set represented by 1 and the minimum represented with 0 or 1-. All the other data points are scaled within that range. In this research both non-regularised data and min-max-regularised data is used with the ANN and CNN approach.

3.2.2 Train Test Split of Data

To address the true performance of models it is preferred that the model performance is tested on unseen data. This also validates the model before it is used. This unseen data is created by splitting all the data in a train set and a test set. The train set will consist of 80% of the original data set and the test set will consist of the other 20%. First, random sample of the size of 80% of the size of the original data. All the other points are appointed to the test set. While *Flach (2012)* proposes a test set size of 10%, in this research there is chosen for a bigger test set. Because the training of the models is computationally very heavy and thus takes great time, there is no cross validation. To compensate for this fact a bigger test size is chosen. Furthermore, there is plenty of data, so the training will not be compromised. And this way the test set gets twice as big, which makes the results of the test set more reliable.

3.2.3 Set Hyper Parameters

ANNs and CNNs have multiple hyperparameters. Linear regression does not have hyperparameters other than the model itself and the loss function. The hyper parameters must be set, this is a delicate process. By varying the parameters, the model performance can increase or decrease. Since, the parameters can be varied in unlimited ways, it is good to map how changes in hyperparameters affect the performance of the model. This can be done by grid search *Pontes et al. (2016)*, random search, or varying only one hyper parameter at the time.

In grid search a *n*-dimensional, with *n* the amount of tuneable hyperparameters, grid is created. The model is trained with the setting corresponding to the place in the grid. Every next step the settings are changed in the direction of one of the parameters. The setting of hyperparameters that yields the best performance is chosen. Random search makes random jumps to other places in the parameters space. Varying the neural network hyperparameters by hand also yields a good result, since natural persons have the ability to make 'educated guesses'. In this research there is chosen to vary the hyperparameters by hand, since the parameter space is so big and the data set large, the computation time would exceed the research time.

3.2.4 Training and Validating the Model

Training the model is a simple process. Since the data is known, the model is defined and the hyperparameters are set. The trained model yields an outcome model. This model then has to be verified.

This verification process can take place in many ways as described in subsection 3.2.2. In this research it chosen to predict the test set and calculate the MAE in comparison to the true values. The model with the lowest MAE compared to the true data is the best performing model. MAE is chosen because it is very explainable. In short MAE states that the predictions will, on average, be off by margin of the value of the MAE.

Another verification step is to check if the model is not 'overfitting'. Overfitting is when the model fits itself too much to the train data and thereby yields a worse performance on unseen test data. This can be checked by comparing the performance on the test set and the training set. If the performance on the train data is significantly better than the performance on the training set, the model is likely to be overfitting. Since in this research interpolated data is used, the model is also tested versus a subset of the true data. To make this possible some time points in the data that are looked for where all sensors have measurements within an acceptable time span. This is only done for the best performing methods, since these models will be used in further applications.

3.2.5 Compare Performance of Different Models

After all models and architectures are tested the performances of the models are compared to each other. The results of this are presented in paragraph 4. There is no standardised data set or standardised algorithm the model can be compared too. This means that one of the models that will be tested will act as a baseline model. The architecture of the baseline model will be described in section 3.3. It is important to note that comparisons between models are only sensible if the same kind of measure is used for all models. In this research this is the MAE.

3.3 Tested Model Set-ups

3.3.1 Baseline Model

The baseline model is the simplest and most naive model. It uses a linear regression method, with only engine-power as input. Intuitively this method should work, since power output should be the most influential factor on speed. For this linear regression to work the features that have collinearity between each other should be omitted from the analysis. The features that are omitted, because of collinearity, for this linear model are thruster 2 and 3 since they are strongly co-linear with thruster 1 and each other. The ordinary least squares (OLS) method is used for fitting the linear regression.

3.3.2 Linear Regression

In the architecture of linear regression models is not much room for changes to improve performance, only the data that is given as input can be altered. In this research the linear regression method that is tested, is trained on all input features but the derivatives of the ship motions. Further the fitting method that is used is the OLS method.

3.3.3 Artificial Neural Networks

As described in section 2.3 there is a big diversity of hyperparameters that can be altered. Also the features of the data that are given as training data can be varied to see if the derivatives of the ship motion have any predicting value. Further the data is given in normalised state and in original state. Following, there is a multitude of activation functions that are tested as well as amounts on neurons in particular hidden layers. In first instance 1 hidden layer neural networks is tested, after deeper neural networks are tested. As explained the hyperparameters are varied by hand.

For computation time purposes, first all models are trained for 50 epochs. An epoch is one complete pass through the training data. The model with the best performances will be trained for 250 epochs to obtain a better performance. The number of neurons in the first layer is originally set at 23 of the input variables. Later greater amounts are tested. When models do not converge in 15 epochs the training is cancelled and the performance is described as non-converging, and the value of the loss functions of the last epoch is given. A list of the tested architectures is provided in table 1. In this list not all varieties of the tested architecture are presented; the best of a particular architecture are. When there is a significant performance difference between for example 17 or 18 neurons in a particular hidden layer, the different architectures will be both be presented.

3.3.4 Convolutional Neural Networks

CNNs share a lot of the hyperparameters with regular ANNs. The extra hyperparameters, needed for CNNs are described in section 2.2.3. The list of CNN architectures is given in Table I. The architecture of the best performing ANNs is used as a skeleton for the initial design of the CNNs. Again here not all architectures are described.

Table I: Description of Tested Models

Model code	Model	Normalisation	Derivatives	Hidden layers	Neurons/layer	Activation functions	Optimiser	Batch size	Kernel size
NN_N_18x_1024_RMSprop_ExDer	NN	No	No	1	18	x	RMSprop	1024	x
NN_MM_18x_1024_RMSprop_ExDer	NN	Min Max	No	1	18	x	RMSprop	1024	x
NN_MM_18x_1R_1024_RMSprop_ExDer	NN	Min Max	No	2	18 1	x relu	RMSprop	1024	x
NN_MM_22x_1R_2048_RMSprop_Der	NN	Min Max	Yes	2	22 1	x relu	RMSprop	2048	x
NN_MM_26S_1R_2048_RMSProp_Der	NN	Min Max	Yes	2	26 1	Sigmoid Relu	RMSprop	2048	x
NN_MM_26S_1R_2048_Adam_Der	NN	Min Max	Yes	3	26 1	Sigmoid Relu	ADAM	2048	x
NN_MM_28S_1R_512_Adam_Der	NN	Min Max	Yes	3	28 1	Sigmoid Relu	ADAM	512	x
NN_MM_26_14S_1R_2048_RMSProp_Der	NN	Min Max	Yes	3	26 14 1	Sigmoid x Relu	RMSprop	2048	x
NN_MM_26_14S_1R_2048_ADAM_Der	NN	Min Max	Yes	3	26 14 1	Sigmoid x Relu	ADAM	2048	x
NN_MM_26_14S_5S_1R_2048_ADAM_Der	NN	Min Max	Yes	4	26 14 5 1	x Sigmoid Sigmoid Relu	ADAM	2048	x
CNN_MM_26S_F_1R_2048_ADAM_Der_3	CNN	Min Max	Yes	2	26 F 1	Sigmoid Relu	ADAM	2048	3
CNN_MM_26T_F_1R_2048_ADAM_Der_3	CNN	Min Max	Yes	2	26 F 1	TanH Relu	ADAM	2048	3
CNN_MM_26R_F_1R_2048_ADAM_Der_3	CNN	Min Max	Yes	2	26 F 1	Relu Relu	ADAM	2048	3
CNN_MM_26R_F_1R_2048_ADAM_Der_5	CNN	Min Max	Yes	2	26 F 1	Relu Relu	ADAM	2048	5
CNN_MM_26_14R_F_1R_2048_ADAM_Der_5	CNN	Min Max	Yes	2	26 14 F 1	x Relu Relu	ADAM	2048	5
CNN_MM_28_15T_F_1R_2048_ADAM_Der_5	CNN	Min Max	Yes	2	28 15 F 1	x Tanh Relu	ADAM	2048	5

4. Results

4.1 Baseline and Linear Regression Model

As described, for linear regression models to work first the values of vector a must be calculated using the model. After the base model is fitted the parameters of the base model are as follows: a = [2.024, -4.581e-04, -1.5099e-03, -1.206e-03, 1.131e-03, 1.866e-04]. The mean absolute error (MAE) of this model is 2.198 kn. This is not very precise given the range of the true values lying between 0 and 30. While the values of the predicted values roughly lie between 0 and 5. This states that the model does not fit well, but it does provide a good starting point from where the optimisation models can start. The linear regression model with all data (except the derivatives of ship motions) as input was fitted, Table II. When observing the predictions of this model over the time span, Fig.4, one thing stands out. There are negative speeds predicted, which is not good. Although there are no linear correlations found between the independent and dependent variables this model performs well with an MAE of 0.5512. This is a significant increase in performance from the baseline model. Also the influence of the ship motions has negative coefficients, i.e. when ship motions get more extreme the predicted speed of the ship goes down. This seems logical, as extreme ship motions imply extreme weather. As explained, this affect the resistance of the ship, decreasing the speed. The expectation is that this model cannot be improved significantly anymore; for further performance increase, other models and methods should be used.

Table II: Parameters of Fitted Model

Intercept	0.34556	KMT_thruster_1_pitch	-0.00171	KMT_thruster_4_power	0.00059
draught fore	0.05085	KMT_thruster_4_pitch	-0.00952	KMT_thruster_5_power	0.00038
draught aft	-0.01709	KMT_thruster_5_pitch	-0.00481	KMT_thruster_6_power	0.00009
trim	-0.51743	KMT_thruster_6_pitch	0.02035	KMT_thruster_7_power	-0.00028
list	0.13808	KMT_thruster_7_pitch	0.01552	heave	-0.3261
KMT_thruster_4_azimuth	-0.00092	KMT_thruster_1_power	-0.00079	pitch	-0.03288
KMT_thruster_5_azimuth	-0.00065			roll	-0.02212

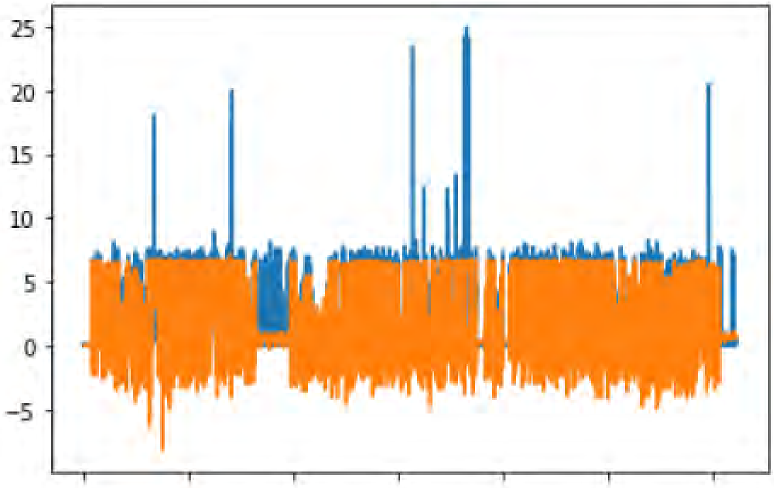

Fig.4: Results of Linear Regression over Interval

4.2 Results of ANNs and CNNs

The best performance reached with linear regression is a MAE of 0.55. The expectation is that the machine learning methods will outperform these linear regression models. The training errors and ultimate test set errors are presented in table 3. The increase of performance once the sigmoid activation function is deployed is remarkable. This can be explained by the non-linearity of speed and resistance. As can be seen the tanh activation function is also tested, but yielded similar to worse results. Furthermore, it occurs the derivatives of ship motions do not have predictive value on their own. They need a non-linear activation function in the base of the network to exploit their full potential. Also the optimiser seems to be of great influence when training for 50 epochs.

Table 3: Results of Machine Learning Approaches

Model code	Training error	Test error
NN_N_18x_1024_RMSprop_ExDer	0.4892	0.4862
NN_MM_18x_1024_RMSprop_ExDer	0.4834	0.4831
NN_MM_18x_1R_1024_RMSprop_ExDer	0.3835	0.3838
NN_MM_22x_1R_2048_RMSprop_Der	0.3835	0.3868
NN_MM_26S_1R_2048_RMSProp_Der	0.2719	0.2746
NN_MM_26S_1R_2048_Adam_Der	NC (1.74)	NC
NN_MM_28S_1R_512_Adam_Der	0.2450	0.2413
NN_MM_26S_1R_2048_RMSProp_Der Trained for 250 epochs	0.2354	0.2422
NN_MM_26_14S_1R_2048_RMSProp_Der	0.2372	0.2357
NN_MM_26_14S_1R_2048_ADAM_Der	0.2260	0.2230
NN_MM_26_14S_5S_1R_2048_ADAM_Der	0.2223	0.2227
CNN_MM_26S_F_1R_2048_ADAM_Der_3	NC (1.74)	NC
CNN_MM_26T_F_1R_2048_ADAM_Der_3	0.2871	0.2853
CNN_MM_26R_F_1R_2048_ADAM_Der_3	0.2635	0.2626
CNN_MM_26R_F_1R_2048_ADAM_Der_5	0.2537	0.2548
CNN_MM_26_14R_F_1R_2048_ADAM_Der_5	0.2465	0.2482
CNN_MM_28_15T_F_1R_2048_ADAM_Der_5	0.2366	0.2365

In the ANN model with 2 hidden layers with sigmoid activation function on the first layer the model does converge with RMSprop but does not converge with the ADAM optimiser. The batch size had to be altered and the architecture of the network had to be changed slightly to get a converging model. Also the increase of performance can be up to and even more than 4% when only changing the optimiser. This is clearly visible in the models with 2 layers with sigmoid activation on the first layer. Adding more layers will not work. The increase from the model NN MM 26 14S 1R 2048 ADAM Der to model NN MM 26 14S 5S 1R 2048 ADAM Der is roughly 0.14% the number of parameters and thus the required computation times goes up.

Analysing the results of both models NN MM 26S 1R 2048 RMSProp Der, illustrates training a simpler model for greater time can cause overfitting. The performance on the training set is better than the performance on the test set. Also, the CNN model with sigmoid activation function does not converge. This could be because, the sigmoid function maps all input to a value between 0 and 1 while the tanh function maps between -1 and 1. Furthermore, the computation time of the CNN is longer than that of their ANN counterparts. This increase is up to a factor six. Increasing the kernel size, while not significantly increasing the computation time, does increase the performance of the model. Overall, more ANN models converged than CNN models. Small changes in the number of filters per layer could induce non convergence. In CNN models a significant improvement is found when the model is made more complex, with different layers.

The NN MM 26S 1R 2048 RMSProp Der model behaves as expected and converges. The same pattern is found in all ANN methods that converge. All converging CNN methods converge likewise. What can be seen is the difference in convergence speed and the shape of the convergence plot between the Adam optimiser and the RMSprop optimiser. The Adam optimiser converges faster at the beginning. The loss function derivative goes to zero over time, while the RMSprop loss function behaves as a straight line from epoch 10 on.

4.3 Model Performance Comparison

There are a couple of important trends that can be picked up from the comparison. More complex models perform better than the less complex models. The CNN do not perform significantly better than the ANN, in some instances they perform worse. The ADAM optimiser the convergences quicker and further than the RMSprop optimiser, as can be seen in Fig.8. When comparing models that use standardised data with models that used non-standardised data, it can be concluded that the models using standardised data converge quicker, but do not perform better.

Table IV: Approximate Computation Time for Certain Models

Model code	Approximation of computation time
Linear regression models	<1 min
NN_N_18x_1024_RMSprop_ExDer	5 min
NN_MM_18x_1024_RMSprop_ExDer	5 min
NN_MM_18x_1R_1024_RMSprop_ExDer	5 min
NN_MM_22x_1R_2048_RMSprop_Der	5 min
NN_MM_26S_1R_2048_RMSProp_Der	10 min
NN_MM_26_14S_1R_2048_ADAM_Der	15 min
NN_MM_28S_1R_512_Adam_Der	25 min
CNN_MM_26S_F_1R_2048_ADAM_Der_3	30 min
CNN_MM_26R_F_1R_2048_ADAM_Der_3	30 min
CNN_MM_26_14R_F_1R_2048_ADAM_Der_5	2.5 hours
CNN_MM_28_15T_F_1R_2048_ADAM_Der_5	2.5 hours
NN_MM_26_14S_1R_2048_ADAM_Der 250 epochs	80 min
CNN_MM_28_15T_F_1R_2048_ADAM_Der_5 250 epochs	4 hours

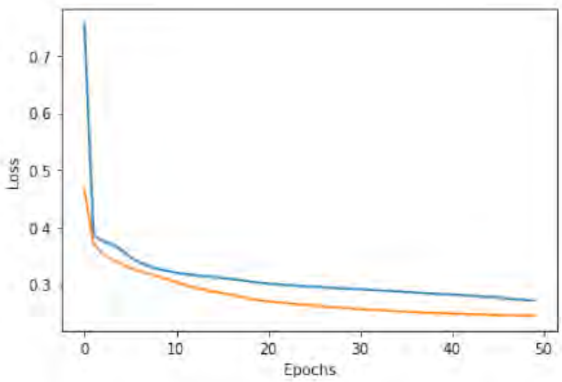

Fig. 8. Convergence per Epoch for RMSprop (Blue) and Adam (Orange) Optimisers

In Table IV the rough estimates of training time per model is presented. Taken these computation times into consideration the artificial neural network model with code NN MM 26 14S 1R 2048 ADAM Der is the best model in this research.

4.4 Final Validation and Improvement of Best Models

To unlock the full potential of the models, the models NN MM 26 14S 1R 2048 ADAM Der and CNN MM 28 15T F 1R 2048 ADAM Der 5 were trained for 250 epochs. The performance of the CNN model increased to 0.2274 on the training set and 0.2270 on the test set. The ANN model performance increased to 0.2151 on the training set and 0.2150 on the test set. This is very good in comparison to the baseline model and also the first linear model. The MAE of best linear regression method is approximately 2.5 bigger than the MAE of these two methods. As described in section 4.3 the 250 epoch version of the best performing models are also tested.

The performance of the NN MM 28S 1R 512 Adam Der model trained for 50 epochs is 0.1845. This is a better performance than on the test set of the interpolated data. This is a very promising result. Especially since the model will be used on real life data. The CNN MM 28 15T F 1R 2048 ADAM Der 5 trained for 250 epochs had an performance of 0.2059 on the true test set. Also this model shows an increase in performance which is a positive sign and is another implication that the models are not overfitted to the interpolated data. This implies the interpolated data are a good representation of the true data. The performance of the NN MM 26 14S 5S 1R 2048 ADAM Der on the true data set is 0.2003. This is worse than the NN MM 28S 1R 512 Adam Der model but still performing better on the true data set than on the training and test set from the interpolated data. The fact that all these models perform good on the true data set implies that no overfitted models were created.

5. Discussion of Results

5.1 Novel Approach

This research opens the door for a new way of estimating ships speed during different operational profiles with data from on-board sensors. The developed method is industry wide applicable, more accurate, less expensive and therewith more encompassing and accessible then other methods. This model could be combined with a model that predicts ship motions, based on environmental phenomena and the ships position. Furthermore, the developed model could be combined with an optimiser algorithm to find the most optimal power output for the engines, given predicted weather forecasts and related ship motions. This combination could be used for route optimisation from point to point since speed can be predicted. So optimal power and speed couple could be predicted for the route. This is a very complex problem combining routing problems with ship motion, and speed prediction. This model could also serve as the start of a prediction model, if data of more ships could be used, where hull form parameters would also be given as an input. If this succeeds, the model could be turned into a more generic model that could be applied to predict the speed of a series of ships.

5.2 Model Usability

The model is suited to be reproduced and used by any shipping company. The training and calculations are based on vessel specific variables. This vessel specific dataset can be altered into any other similar dataset, when training the model for other vessels. Furthermore, the required computational power is very low, the development and training was performed on a normal laptop. Meaning the model could be used on the bridge of a vessel for live operational decision making. Concluding the developed model is generally available and applicable.

5.3 Discussion

During the research there were several assumptions and limitations to the developed model. Critical points of discussion with regards to the assumptions and limitations include:

- Due to the nature of the original data, interpolated data was used. Since there is always a chance of information loss with interpolation this is ideally prevented. Although the models have a decent performance on the 'true' data, this true data is also an interpretation of the real data. Further research might prevent this by actively managing the data gathering procedure.
- During this research there was a lack of certain context data. Historical wind and wave data was not available at the exact position of the ship. When evaluating the outcomes of the models these features could have increased the model performance.
- It is important to note that this model by itself is not capable of predicting the speed of a vessel of a future trip. This because the model takes the ship motion as input, and ship motion is not known in advance.
- In this research field it is very hard to relate the outcome of this study to outcomes of other studies. It is difficult to compare the results of this study to other studies that assess comparable topics. This complicates this particular study because it is hard to map progress on an absolute scale. A standardised validation set would improve this research and the maritime research field as a whole.

6. Conclusion

The goal of this research is to present a way to improve the speed and resistance prediction of ships. This research presents a method, a machine learning approach. The speed over ground of a vessel can be predicted with numerous methods. The best predictions on training and testing data were made by an artificial neural network containing three hidden layers with sigmoid and relu activation functions. The best performance on the 'true' data was reached with a model with one hidden layer with sigmoid activation.

This novel approach for speed and resistance prediction, offers a quick and accurate speed over ground based on operational data. For ship design and ship management companies this is important information, that can be used in ship design or operation. The method developed in this research is inexpensive, generally applicable and proves the concept.

To summarise the findings of this study, it is indeed possible to predict the speed of the ship in operational condition with data from on-board sensors. Next to being an improved speed and resistance prediction method, the successful implementation and validation of machine leaning to predict speed over ground also provided valuable novel insights in machine learning in marine engineering in general. Therewith, contributing to the body of knowledge of data-science in marine engineering.

Recommendations for further research comprise the development of a benchmark model and standardised data set, development of a ship motion prediction model and further development and generalisation of the developed model.

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Eye-Tracking in Maritime Training: New Performance Measures for Immersive Virtual Reality Training Applications

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Abstract

This paper presents novel performance measures using binocular eye tracking within Virtual Reality (VR) and discusses their application in maritime navigation training. There is a sizeable literature already exists regarding how eye tracking can be used to assess trainee's performance and how these measurements can be valuable for both training assessment and feedback. Head Mounted Display (HMD) based immersive VR solutions are emerging to be a promising training medium for professionals across many domains, including maritime industry. Introduction of these new tools in training also create opportunity for new ways of performance assessment and feedback possibilities. This paper treats one of the main issues involved in the practical realization of VR technology in maritime training: performance assessment in VR simulators and describe a concrete concept of assessment and feedback techniques using eye tracking (ET) with an example of utilization of such concept in maritime navigation training.

1. Introduction

Virtual Reality (VR) is a promising medium for professional training applications, *Renganayagalu et al. (2021)*. VR technology has long been considered as having great potential in education and training. However, due to the technological and economical limitations, it couldn't gain widespread popularity within education and training until recently. This has now changed post the introduction of new commercial VR headsets. The latest advancements in computing power, display technologies and 3D graphics have driven the development of affordable, high quality immersive VR hardware and applications. Apart from the initial wave of entertainment applications, immersive VR is finding a place in education and training applications due to the realistic and immersive experience it offers.

Maritime industry has used simulators as one of its cornerstones of training for many decades. Despite the popularity of simulators to deliver training, evaluating the training outcome are largely limited to subjective self-reports and feedback from the instructors. It is widely accepted among educators and researchers in the field that there is more to be done in training assessment. A recent systematic review in the field revealed the shortcomings of current simulator-based training and assessment which could have implications on the safety hazards for the shipping industry, *Sellberg (2017)*. With the introduction VR training simulator comes new challenges in training assessment & feedback, At the same time it also provides new opportunities for assessment as well. This research will introduce a new approach to assessment of trainee performance in simulation enabled and supported by VR technology.

2. Background

2.1. Simulator Training

The goal of a simulation-based training (SBT) methodology is to provide systematic and structured learning experiences to the students. In the education and training context, simulations are used to improve knowledge, trainee performance, and assess competence. Traditionally, training for safety critical domains such as maritime is accomplished via on-the-job training (OJT). However, due to limitations of the OTJ especially for demanding operations because of the safety implications and associated costs, SBT is a preferred over it. SBT is a promising method of training skills due to its realistic, flexible environments where students can gain new knowledge, test this knowledge by applying them to simulated tasks, and master complex material by repetition, *Menaker et al.(2006)*. Simulators allow students to make errors and learn from their mistakes in a controlled environment, free from real-world consequences, *Salas et al. (1998)*. Earlier research have shown that SBT provides an effective alternative to OTJ, *Farmer et al. (2017)*. Because of the benefits associated with SBT, research should examine ways to appropriately incorporate instructional interventions so that the training and cost effectiveness of these systems can be optimized.

2.2. Role of performance assessment and feedback in SBT

The effectiveness of the SBT methodology is dependent on the quality of performance measurement practices in place, *Salas et al. (2012)*. The success of any SBT depends upon effective transfer of skills to the corresponding real-life system. This could only be ensured with proper performance assessment post training in simulators. Performance measurement during SBT must be diagnosed; that is, the causes of effective and ineffective performance must be determined. This diagnostic measurement drives the systematic decisions concerning corrective feedback and remediation, *Farmer et al. (2017)*.

Feedback is information provided to a trainee about their task performance. Feedback is a necessary instructional event that should have characteristics of being both informative and tailored, *Gagne et al. (2005)*. Timely, constructive, and diagnostic feedback makes the training more useful. Feedback could vary to different degrees of information, but at least it should provide information to the trainee to learn correct responses to particular stimuli in the task.

2.3. VR-based simulator training

Virtual Reality (VR) is when a person ceases to perceive one's own surroundings and experiences the computer-generated environment immersed through a dedicated headset. VR allows users to interact with the computer-generated world, where the user's natural sensory perceptions are fully/partially replaced with a digital alternative. The key added value of VR lies in the immersion offered by it (Psotka, 1995). "Immersion" or "Presence" felt by the users, is the sense of being present in the simulated virtual environment, *Witmer and Singer (1998)*. High presence means the user has very little or no disbelief in the virtual environment they are experiencing. This "sense of being there" enables experiential learning through virtual environments, which leads to positive transfer of knowledge, *Stevens and Kincaid (2015)*. VR provides a controlled learning environment in which users can navigate, explore, manipulate and inspect the objects and their response in real-time. This explorative learning environment enables users to learn through experimentation. Immersion of a VR system is comparable to the physical fidelity of the simulators as both immersion and physical fidelity could be objectively measured. Since the simulation environment in VR is fully digital, the system is relatively cost-efficient and portable compared to the traditional simulators. The flexibility to make different simulation scenes, environments, scalability, smaller footprint and convenience of training from remote locations makes VR an interesting technology for simulator training.

2.4. Issues with using VR in training

Despite the numerous benefits, VR simulators also have significant issues to be addressed before adapting them for training. There are unique challenges associated with the VR technology itself such as maturity of the technology, acceptance of technology among the users, cyber sickness, etc. Another obvious issue is the role of instructor in VR simulator training. Instructors play a crucial role in the maritime training process. Currently performance assessment of learning complex tasks in simulators is performed by the instructors. A human instructor is highly effective because he/she is able to assess the prior knowledge of students, potential misunderstandings, and confusion, then adapt the instructional support and feedback to enhance the learning experience accordingly, *Anania (1983)*. With the current state of the art of VR technology, it is hard for the instructor follow student performance because both the student and instructor are not in the same virtual environment, even if they locate in the same room. There are virtual co-location solutions available for this problem, but they aren't ideal since the users are represented by avatars. Also, the HMD covers part of the student's face, so it is not possible for the instructors to follow where the student is looking. Especially for visually demanding tasks such as navigating a vessel, instructor orienting towards the students' gazes for determining their methods for assessing the situation is very important, *Sellberg (2018)*. Eye tracking (ET) integrated with VR can contribute to resolving this challenge. Vision being the dominant sensor in information processing for humans, ET could provide more insight into student's performance to the instructor. There is a sizeable literature already exists regarding how eye tracking can be used to assess trainee's performance and how these measurements can be valuable for both training assessment and feedback, *Tien et al. (2014)*.

In addition, the challenges associated with performance assessment and feedback in traditional SBT is also applicable to VR simulator. According to *Farmer et al. (2017)* there are four fundamental Problems in Performance measurement in SBT: The hidden and embedded nature of performance, lack of a general theory of human performance, how to determine the validity of performance measures and how to establish the criteria for performance. Through this research we try to solve some of the above problems in a maritime VR training simulator.

VR technology is touted to offer decentralised, remote training possibilities. In order to take advantage of the self-regulated, de-centralised training opportunities, the training system should have intelligent tutoring and feedback agents. i.e., the assessment and feedback should be automated and adaptive in such a way that it keeps the students engaged and help them achieve their learning goals.

3. Development and integration of ET measures for the VR navigation trainer

3.1. Eye tracking applications

Eye tracking (ET) is the measurement of a person's gaze movement. By directing a safe, invisible light source at a subject's eye and then using a special camera to track the reflection, it can interpret precisely where or what the person is looking at. The main benefit of an ET system is that it provides a continuous flow of information about the user in real time that can be used to assess the user's attention and/or their cognitive state, *Liu et al. (2011)*. When combined with a precise understanding of the real-world environment, such as the ship bridge and navigation training scenario, eye tracking can be used in real-time (see figure 2) or recorded and played back to help assess exactly how the student is processing their visual surroundings. ET in VR simulators could be used in 4 ways, 1. for reducing VR system's rendering workload using foveated rendering, 2. as an interaction tool, 3. as an objective assessment tool, 4. as a feedforward training & active feedback tool to trainees. Foveated rendering is out of scope for our research. Despite the usefulness, there is a well-known Midas touch problem for using ET as an interaction tool, *Majaranta and Bulling (2014)*. So, for our training purposes we have chosen to focus on the other two applications of ET in VR.

3.2. Eye tracking in VR HMDs

Current eye tracking in VR HMDs is video based. The system has an infrared light source and cameras facing towards the user's eyes. The cameras record eye movement by capturing infrared light reflection off the pupil. Gaze detection is performed by matching the black pupil ellipse in each video frame and calculating its center. Mapping of gaze to screen coordinates is performed by fitting eye models and gaze vectors in the 3D space of the VR scene, *Swirski and Dodgson (2013)*.

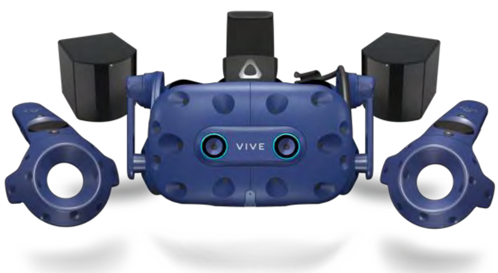

Fig.1: HTC Vive pro eye with built in ET

For our research we have used HTC's vive pro eye HMD (Figure 1). It has an integrated binocular eye tracker that has 120Hz sampling frequency. The accuracy of the ET is between 0.5^0 to 1.1^0 according to HTC's official website. The HMD uses 5-point calibration for accurate gaze tracking of individual users. The ET outputs timestamp, gaze origin, gaze direction, pupil position, pupil size and eye openness as data. From this raw data different gaze metrics are derived.

3.3. Eye tracking measures for performance assessment

Following are the three important metrics used in the Eye tracking research,

- <u>Fixation:</u> It is the time taken for processing image by fovea. Fixations are minor eye movements around a point of interest. These minor eye movements are needed to keep points of interest in focus. Fixation durations vary from 100-600 ms, *Holmqvist et al. (2011)*.
- <u>Saccade:</u> It is the time interval between two fixations. Saccades are rapid eye movements changing the fovea to a new location of interest. Saccade happens in between two fixations and is the fastest known body movement. Saccades usually lasts less than 150 ms and on average is about 20-40 ms. For recording saccades accurately, eye trackers with higher sampling frequency are required.
- <u>Scan path:</u> It is the sequence of fixations arranged in space. Scan paths provide insight about the attention sequence of the user.

From the fixations and saccades there are many gaze metrics derived such as dwell time, fixation frequency, average fixation duration, number of visits and revisits. These are some of the key performance indicators (KPIs) from the gaze measures. These metrics provide valuable insight into user's (students in this case) gaze behavior when visualized in the pre-defined Areas of Interest (AOI), Fig.3. AOI are defined with the help of Subject Matter Experts (SMEs) with the elements/targets that are relevant for the specific training task. Once the AOIs are defined, different KPIs such as entry time, dwell time, average fixation durations, frequency of fixations in different AOIs are calculated for the students. These measures could then be compared with expert gaze data for the particular scenario to estimate the skill level of the student. The analyses could also be used to measure the skill improvement of the student by comparing their gaze metrics pre and post training.

Below are some of the KPIs used in AOIs, *NN (2014)*:

- Gaze duration: It is the cumulative duration and average spatial location of a series of consecutive fixations within an AOI.
- Sequence: Order of gaze hits into the AOIs based on entry time.
- Entry time: Average duration for the first fixation into the AOI.
- Dwell time (in ms and %): Average (ms): (all fixations and saccades within an AOI for all selected subjects)/ number of selected subjects. Average (%): dwell time average *100/ (current time- start time)
- Hit ratio: How many subjects out of the selected subjects looked at least one time into the AOI
- Revisits: Average revisits = (Number of glances divided by selected subjects with at least one visit)
- Average fixation: Sum of "average fixation time per subject in an AOI" divided by number of selected subjects
- Fixation count: Number of all fixations for selected subjects divided by number of selected subjects.

To analyze the ocular behavior (visual perception) of the student, Dwell time, attention maps and sequence charts are useful. For analyzing the scan path events Look-backs and backtracks are used. In addition, pupil size and blink rates are also recorded, which could be studied further, if required. These measurements such as pupil diameter, frequency of blinks, duration of blinks, and number of blinks are also used for deeper analysis of cognitive processing and stress in this system, *Van Orden et al. (2000).*

Fig.2: Real time gaze tracking in VR simulator

Fig.3: Marking of AOIs in the VR bridge model

5. Conclusion and future work

This paper has discussed the application and potential benefits of ET in VR-based maritime navigation simulator. The next step is to carry out an empirical investigation to validate the assessment and feedback methodology. Our prototype is able to visualise the student's gaze in real time and also measures various gaze data such as fixations, saccades, etc. the next step is to visualise them in more intuitive way to the instructors and students, so that they can interpret what it means.

Overall, eye-tracking is a highly valuable tool to investigate various aspects in VR training simulators. The possibility to model different environments and control every aspect of them is highly valuable in research and should be further exploited in the future. In conclusion, we believe that eye-tracking in VR has enormous potential for performance assessment and feedback for students.

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Energy Efficient and Safe Ship Routing using Machine Learning Techniques on Operational and Weather Data

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Abstract

This paper presents a method for energy efficient routing of a symmetrical electrical car ferry in Norway. Historical and operational data from the ferry and environmental data (wind, current, and waves) have been used to develop a machine learning model that predicts the energy consumption. Data from more than 2000 trips have been used for training, validation, and testing of the model. By combining weather forecast and the established energy prediction model it is possible to propose more energy efficient route during the transit phase. Energy saving up to 3% are achieved on a selection of representative routes.

1. Introduction and motivation

Following up the UN's sustainable development goal to combat climate change, the International Maritime Organization (IMO) has adopted mandatory measures to reduce emissions from shipping by introducing the Ship Energy Efficiency Management Plan (SEEMP) for all ships (IMO, 2019). For this reason, a good measure of the ship's energy consumption under different operational and environmental conditions is highly valuable and urges for improved voyage planning. One of the main challenges of voyage planning is to determine the optimal route that gives the lowest energy consumption. Optimal routing of vessels has a large potential for energy, and hence cost and emission, savings and is estimated to be around 7% for the global fleet, *Lindstad (2013)*. (*Lindstad (2013)* reports the estimated savings in terms of CO2. Although the here presented work is based on an emission-free vessel, it is reasonable to assume that emission savings for conventional vessels translate to comparable energy saving for electric vessels since the emission reduction is tied to reduced fuel consumption.) Today's solutions for route planning and optimisation are usually based on weather forecasts and vessel models, describing its behaviour as a reaction to different environmental forces. Examples of commercially available solutions of this type are StormGeo's S-Suite, https://www.stormgeo.com/products/s-suite/, or Navtor's weather routing module in NavStation, https://www.navtor.com/weatherservices.html, to mention but a few. Common for these solutions is that they are used for large-scale planning of routes (e.g. avoidance of storms when crossing Atlantic), meaning that the hydrodynamic model of the vessel can be quite simple.

For vessels servicing a fixed short-distance route (e.g. car ferries), large changes in route are not feasible. Additionally, alterations in route are limited by the area in which safe navigation is possible, e.g. due to sea depth. Still, small adjustments of the course and/or speed may yield a few percent energy savings. Given the high frequency such routes typically exhibit (daily, up to 20+ times a day), a percentwise small saving on each trip will accumulate to a significant amount over the course of the year. Because of the limited possibilities to adjust course and or speed owing to strict timetable requirements, a good understanding of the impact of environmental disturbances on energy consumption is imperative for successful route optimisation in such cases.

For Norwegian ferries, fuel accounts for approximately 20% of the overall operational cost and is, after wages, the second largest contribution factor, *Aarhaug et al. (2017)*, https://www.ssb.no/a/kortnavn/skipinne/tab-2008-01-29-02.html. Hence, a reduction of energy consumption will have a significant impact on the overall expenditure of ferry companies. When referring to the energy consumption, we focus on the propulsion energy alone. Hotel loads are not considered in the optimisation at current stage. For the optimisation, the objective is to minimise the energy consumption and reach the destination within the requested time of arrival (RTA). Comfort is not included as an optimization criterion.

However, low energy consumption is often related to low environmental disturbances, which naturally coincides with higher comfort.

For the ferry route used in this work, transit is the longest and most energy consuming phase (75-80% of the overall propulsion energy used for an individual trip, Fig.2) with the most intricate interplay between vessel and environmental forces, while acceleration and retardation are much shorter and account for a significantly smaller amount of the total energy consumption of each trip. Hence, we treat acceleration and retardation as fixed for scope of this initial study and focus on transit alone.

The interplay between ship performance and various influencing factors is difficult to model using model tests or numerical methods, *Parkes et al. (2018), Petersen et al. (2012).* On the other hand, more and more sensor data have become available and machine learning (ML) techniques have proven to be able produce good quality estimates, *Parkes et al. (2018), Yoo and Kim (2017)* provided a vast enough dataset of sufficient quality. Hence, we choose a ML-based approach to estimating energy consumption, while designing the optimisation loop generally enough to be able to adopt to other types of energy consumption estimators especially for cases where no historical data are available.

The here presented work is based on a symmetrical electric car ferry operating in Western Norway. A trip takes approximately half an hour.

2.Related work

An overview of the state-of-the-art optimization methods used in weather routing has been presented in *Walther et al. (2016),* where the Genetic Algorithms, Calculus of Variations, and Dynamic Programming are some of the methods mentioned. A mixed-integer nonlinear optimization problem has been used to find the optimal route and speed that minimizes the fuel consumption, *Tanaka and Kobayashi (2019).* A weather routing system based on a multi-criteria setup (travel time, added resistance, and safety) using a generalization of the Dijkstra algorithm has been developed, *Fabbri and Vicen-Bueno (2019).* Evolutionary multi-objective optimization of ship routes using real weather predictions has been studied in, *Szlapczynska and Szlapczynski (2019).* Many of the related works for weather routing revolve around long-distance route optimization where a large reduction in energy consumption can be achieved by avoiding the roughest environmental conditions. However, a considerable reduction of energy consumption can also be achieved for short-sea shipping, due to the high frequency of voyages. *Grifoll et al. (2018)* has developed a weather routing system for short-sea shipping based on a pathfinding algorithm with the use of meteo-oceanographic predictions.

With large amounts of operational ship data and environmental data available, there has been an increased interest in using machine learning methods for estimating the energy consumption, *Bui-Duy and Vu-Thi-Minh (2021), Parkes et al. (2018), Petersen et al. (2012).* Often, regression models are used to predict the energy consumption, e.g., the nonlinear regression model developed by, Yoo and Kim (2017) to estimate the engine power using the engine RPM, weather data, draft, and trim as inputs. Deep neural networks have also been utilized to estimate the fuel consumption of container ships*, Bui-Duy and Vu-Thi-Minh (2021)* and *Parkes et al. (2018)* using the ship velocity and weather data as inputs.

In cases where we do not have large amounts of operational and weather data, a simulation approach is more suitable. In route and weather optimization simulation, the vessel model lays the foundation, and a lot of effort has been put into developing full featured ship models. With increased availability of computational power, full featured ship models have been proposed to simulate the vessel accurately, *Fossen (2021).* These high-fidelity models usually consist of a large set of differential equations that describe the ship accurately, however the set of differential equations may be computationally demanding to solve and are not practical to apply on simulation horizons longer than a couple of days. Hence, for optimization tasks, simpler models are usually implemented, as shown in *Kobayashi et al. (2015),* where a model-based method is presented for weather optimization for deep sea voyages. *Vettor and Guedes Soares (2016)* on the other hand, presents a complete on-board ship weather routing system. Moreover, the discrete event simulator (DES) Gymir developed by SINTEF Ocean, is an alternative low fidelity simulation model that models important hydrodynamic effects at discrete points in time and space. Gymir is an expansion of the method presented in *Fathi et al. (2013)* and *Sandvik et al. (2018)* and can be used to evaluate ship concepts in realistic conditions given a vessel modelled by the ShipX numerical software package, *Fathi (2018), Fathi and Hoff (2017).* ShipX is based on a 3D-model of the hull and uses potential flow strip theory to compute the residual resistance. Combined with an open water curve for a propulsor, the required power and RPM to attain a speed through water are estimated for any significant height, peak period and mean direction of the waves and average wind speed and direction, *Fathi (2018), Fathi and Hoff (2017).* This simulator can replace a machine learning energy model in the route optimization. Additionally, the simulation can be used to generate synthetic data as input for the machine learning algorithm in the design phase when there is no real operational and weather data available at the cost of increased computational demands.

3. Data collection and system description

This section gives a description of the data collection performed, the modelling of energy consumption as a function of operational choices and environmental conditions, and the optimisation routines used. Energy consumption is a sensitive parameter for ferry companies. hence the presented data have been anonymised removing explicit reference to location, e.g. coordinates, and energy consumption is not reported in absolute numbers, but relative to reference values, e.g. the average energy consumption for the route or the energy consumption before optimisation.

3.1 Data collection

In order to relate the energy consumption of the vessel to operational choices (e.g. chosen route and speed) and environmental conditions, we log in excess of 180 signals from the on-board system of a car ferry. All signals are logged at a sample rate of 1 Hz and are stored to file. These signals entail route related information such as speed and course over ground (SOG and COG), the electrical power consumed by propulsion system, down to detailed information about propeller pitch angles, to mention but a few. (More precisely, we measure the electrical power consumed by the electric motors driving the propulsors.)

In addition to the choices of route and speed, the energy consumption of a vessel is determined by the environmental condition under which it operates, namely waves, wind, and currents. Environmental conditions are inherently multiscale and the predominant conditions in a wider area are hence difficult to capture with in-situ point measurements, e.g. an anemometer mounted on the vessel. Thus, we resort to data produced by meteorological forecasting models, that cover larger areas, at the price of reduced spatial and temporal resolution. More specifically, we use a separate wave, https://thredds.met.no/thredds/fou-hi/mywavewam800.html, wind, https://thredds.met.no/thredds/catalog/metpparchive/catalog.html, and current, https://thredds.met.no/thredds/catalog/fou-hi/norkyst800m-1h/catalog.html, model made freely available to the public by the Norwegian Meteorological Institute, under CC 3.0/4.0 BY license, cf. https://www.met.no/en/free-meteorological-data/Licensing-and-crediting and the landing pages for the respective data sets. Each of the models has a temporal resolution of one hour and a spatial grid resolution of 800 by 800 for the wave and current and 1000 by 1000 m for the wind model. For a more thorough description of the individual models, we refer to the documentation available on the landing pages for the respective data products.

The model data are harmonised with the time series collected from the vessel's systems through interpolation. For a given time and position of the vessel, the model data are first interpolated spatially using inverse distance weighted interpolation (using the four grid points closest to the current position) in the two model time steps enclosing the current time stamp. Then, the values are interpolated linearly in time. (Note that the order of interpolation is arbitrary, i.e. performing temporal interpolation first and then spatial interpolation will yield the same results.) Directional variables, e.g. wind direction, are interpolated in the space of complex numbers (using the embedding $[0, 360[\hookrightarrow \mathbb{C};\ \varphi \mapsto e^{i\varphi}$ prior to interpolation).

3.2 Data processing and modelling

Each trip of the ferry can be subdivided into three different phases: 1) the acceleration phase, where the vessel picks up speed, 2) the transit phase, where the vessel speed varies only moderately, and 3) the retardation phase, where the vessel's speed decreases back to zero. This splitting of phases is illustrated in Fig 1.

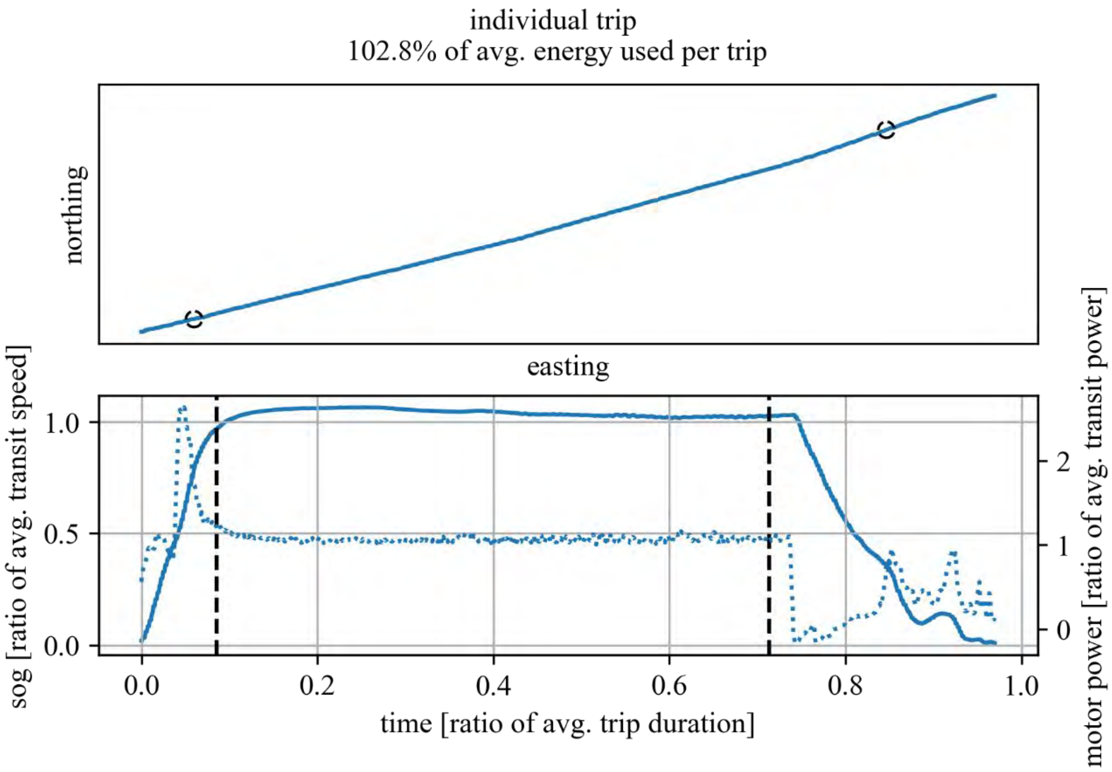

Fig 1: Illustration of splitting of an individual trip into acceleration, transit, and retardation phase. The top panel shows the position of the vessel during the trip. The departure point is in the lower left corner. The bottom panel shows the vessel speed (solid line) and power output of the vessels propulsion system (dashed). Both graphs are normalised by the average values of the respective variables. The black dashed lines (bottom panel) and circles (top panel) indicate the time and position of the start of different phases, respectively.

Accordingly, the data processing consists of the following steps:

1) Each trip is split into an acceleration, transit, and retardation phase, using the SOG profile by fitting a piecewise linear function with three pieces, imposing positive and negative slopes on the first and third piece, respectively.
2) For each phase, the average value of the following quantities is computed: SOG, course over ground, current speed and direction, wind speed and direction, significant wave height, wave peak period, and wave peak direction.
3) In addition, the total energy used for propulsion during each phase is calculated, the duration of the phase, and the total distance covered by the vessel during the respective phase.

After these processing stages, a regression model for the transit phase is developed. The model estimates the total energy used during transit based on average SOG, alongship current and wind speed, significant wave height, and wave peak period. The energy model estimates the energy consumption with a relative error of 7%. (Scaling current and wind speed by the cosine of the difference between current and wind direction and the vessel's course over ground, respectively.)

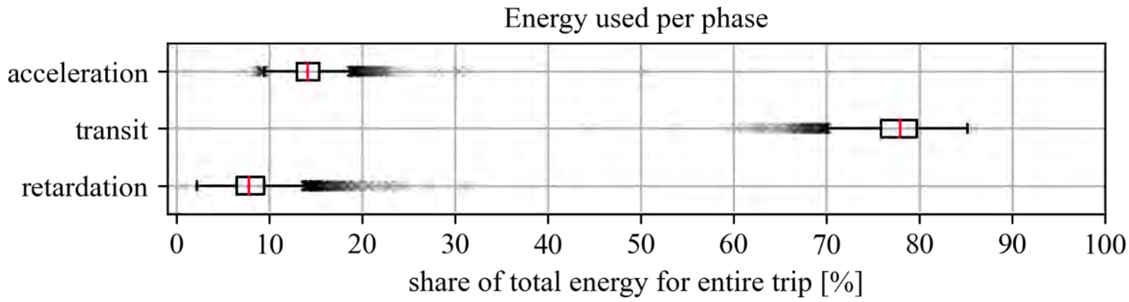

Fig. 2: Distribution of share of propulsion energy used for a whole trip per phase. The distributions are represented using 'boxplots'. The box represents the interquartile range of the distribution (i.e. the central 75% of the data points), the red line the median. Datapoints further then 1.5 time the interquartile range away from the median (indicated by lines extending from the box, called whiskers) are considered outliers and indicated by a marker (x). The figure shows that for the collected data, the acceleration phase accounts for approximately 12-15% of the overall energy consumption, while the retardation phase represents ca. 7-10%. The transit phase typically amounts to 75-80% of the overall energy consumption during a single trip.

Energy estimations obtained from DES Gymir (see Section 2) have been compared to the results of the energy model developed using machine learning with a wide range of weather conditions observed during the data collection campaign. (Wind speeds ranging from 3.6 to 11.7 m/s, and significant wave heights between 0.1 and 0.5 m.) The results indicate that Gymir's estimation error is ranging between 3% to 20%. The machine learning based energy model has an error of 7%, which indicates reasonable agreement between the two energy estimation options.

3.3 Optimisation

In a planning stage, a route is typically defined as a collection of positions along the path of the route, so-called waypoints, and speed to observe in the stretches between waypoints, the so-called legs of the trip. Since the transit phase is the focus of this study, the acceleration and retardation phases have fixed durations and are not considered in the optimisation. The starting point for the optimization is the waypoint at the end of the acceleration, and the stopping point is the beginning of the retardation. Thus, the parameters that are tuned to achieve a minimal amount of propulsion given an initial route with n waypoints and n-1 legs are:

- n-4 x- and y-coordinates of waypoints (n-4 since start and end point are fixed as well as end of acceleration and start of retardation.)
- n-3 velocities (n waypoints yield n-1 velocities, in addition the velocities during acceleration and retardation are fixed.)

For a given set of these parameters, an interpolated trip is generated using linear interpolation of positions between waypoints, and a linear velocity ramp-up and ramp-down during acceleration and retardation, respectively, and piece constant interpolation for the remainder of the tour. Based on the time stamps and positions of this interpolated route, associated interpolated meteorological data are generated, using the steps outlined in Section 3.1. Finally, the interpolated trip is split into its three phases based on the set duration of the acceleration and retardation phase, and the inputs to the energy model in transit are calculated. These steps are repeated for each internal iteration of the optimisation loop. Fig.3 gives a schematic overview of the described steps.

In addition to minimising energy consumption, the optimised route must fulfil other requirements, dictated by time schedule and. The time schedule sets an upper bound for the duration, turning the minimisation problem from a free minimisation to a constrained problem. For a given departure time we can derive the estimated time of arrival (ETA) for the interpolated route using speed and distance between waypoints. Hence, the difference between ETA and the requested time of arrival (RTA) can be added to the unconstrained problem as a penalty term. Negative values indicate arrival before RTA, positive values delayed arrival. Since we only want to set constraints on late arrival, but neither reward nor penalise early arrival the respective term is set to zero if it becomes negative, i.e. for arrivals ahead of schedule. (Transit times will typically yield higher energy consumption, but this effect on the overall energy consumption is already captured by the energy models, and a non-zero penalty term.) Safety limits the geographic area the optimisation has at disposal. We assume that an area that allows safe navigation is specified as a corridor around the proposed initial route given by a distance to either side of the legs. Hence, we introduce an additional penalty term that is the Hausdorff distance between the outline of the safe navigation area and the part of the trajectory of the vessel that lies outside the safe navigation area, first-order Tikhonov regularisation type terms for speed and course over ground, *Aster et al. (2013)*. The fact that changes in course and/or speed are generally associated with increased energy consumption and compensates, to some degree, for not including variational terms, e.g. variance of speed during a phase, in the energy model.

The overall objective function for the minimisation problem at hand is hence defined by the sum of the energy estimation, penalty terms owing to constraints, and regularisation terms. Due to the complex nature of the objective function, we opt for a gradient free optimisation method, namely the well-known simplex method, also known as Nelder-Mead method, *Gill et al. (1982).*

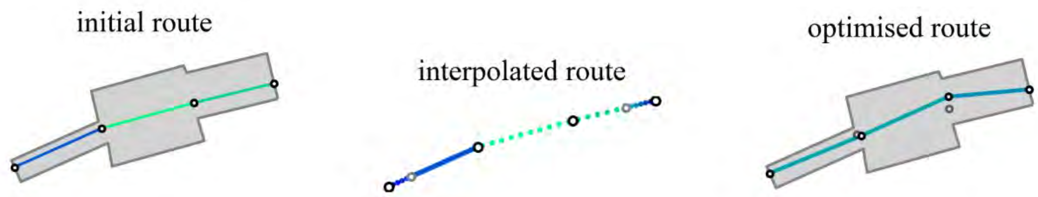

Fig.3: Schematic overview of the steps performed during optimisation. Left: the initial route is given as a collection of waypoints (back circles) and speeds over ground to observe between the waypoints (coloured lines). The colour indicates speed ranging from dark blue for low speeds to light green for high speed), and a polygon defining, the area of safe navigation (grey). Middle: given a number of waypoints, speeds between them, and duration of acceleration and retardation, a regularly sampled time series of positions and speeds is generated. The small grey circles represent the end and start of the acceleration and retardation phase, respectively. This step is repeated after each change in waypoint location, speeds, and acceleration/ retardation duration in conjunction with the iterations of the optimiser. Right: the result of the optimisation process is an updated set of waypoint location and speed (grey circles indicate the initial locations). The locations of the waypoints are constrained by the initially provided save navigation area.

4. Demonstration

In order to demonstrate our approach, we have generated initial routes based on ten logged trips and run our optimisation code. Five of the trips have been selected at random but ensuring that they would span the range of weather conditions observed during the data collection campaign. Then five more trips in the opposite direction in temporal vicinity of the first trip (up to two hours) have been added in order to have a trip in each direction under similar environmental conditions. Trips commencing in the southwestern end of the route are referred to as "outbound", the opposed direction as "inbound". Characteristics of the selected trips are given in Table I with the corresponding waypoints for each trip illustrated in Fig.4. Six of the trips had been taken in calm conditions (out- and inbound trips 1 - 3), two in moderate conditions (4a and 4b), and two in harsh weather conditions (5a and 5b). (The car ferry used in this work operates in sheltered water. Especially wave heights are very limited.) The trips are 7300-7500 m long, and the average speed for the entire trips is 11.7 and 12.3 kn. The RTA is set to be the actual duration of the trip.

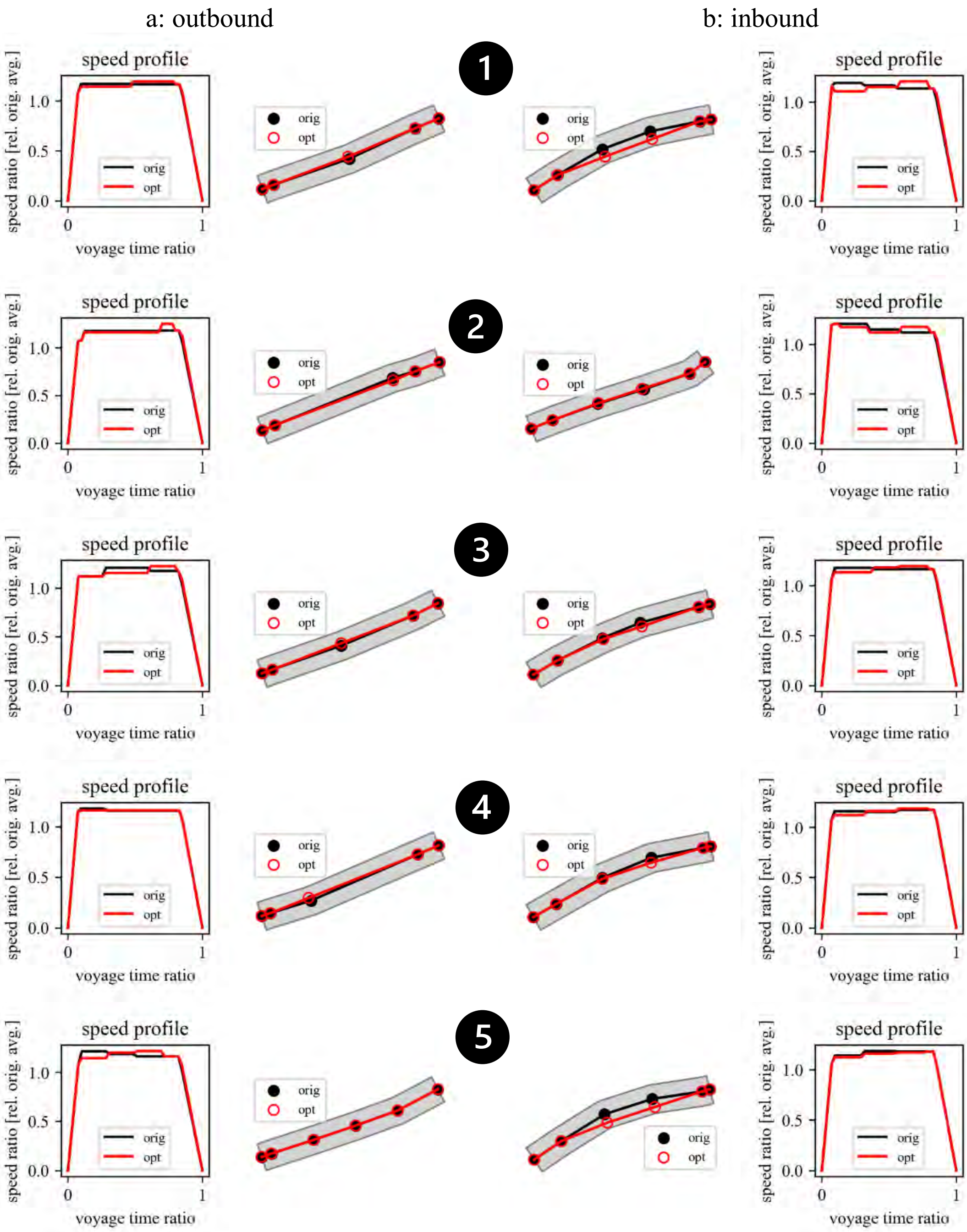

Fig.4: The waypoints of the initial (black) and optimized (red) routes used in the demonstration of our approach. The grey area in the background indicates the save navigation zone. The figures on the left-hand side are outbound trips, with starting point in the lower left corner. The figures on the right-hand side are inbound trips, effected within at most 2 hours from the outbound trip. We see that the changes in the positions are generally small, but distinctively more pronounced for inbound trips and result in a shortening of the travelled distance. We note also subtle changes in the speed profile during transit with a tendency to somewhat decrease the speed in the first part of the transit and a subsequent gradual increase.

Table I: Overview of optimised routes. The first three columns describe the weather condition during the trip, the fourth the direction of the route, and the last the changes to energy consumption as result of the optimisation. Fig.4 shows the waypoints corresponding to the routes.

Trip nr.	Sig. wave height	Wind speed	Wind dir.	Direction	Energy change (opt)
1a	0.10 m	4.4 m/s	21.9°	outbound	-0.3 %
1b	0.12 m	4.3 m/s	17.0°	inbound	-2.2 %
2a	0.09 m	3.6 m/s	80.0°	outbound	-0.3 %
2b	0.08 m	3.5 m/s	74.9°	inbound	-0.4 %
3a	0.14 m	5.0 m/s	194.5°	outbound	-0.3 %
3b	0.17 m	4.9 m/s	192.5°	inbound	-1.0 %
4a	0.21 m	9.8 m/s	69.2°	outbound	-0.1 %
4b	0.22 m	9.8 m/s	70.7°	inbound	-1.2 %
5a	0.53 m	11.8 m/s	257.8°	-outbound	-0.8 %
5b	0.59 m	11.6 m/s	251.4°	inbound	-2.7 %

5. Discussion and future work

The results from optimising ten different routes presented in the previous section indicate that a reduction of up to 3% in energy consumption can be achieved through relatively small changes in course and speed, while maintaining the original schedule. The optimised routes differ from the initially proposed route.

The reported energy savings are based on the estimated energy consumption during optimisation and are hence subject to underlying uncertainty of the energy models. Moreover, it must be assumed that the vessel will be able to follow the suggested optimised route only to a certain degree. How much of the theoretical energy saving can be achieved in real life, will be assessed during a field campaign planned for autumn 2021.

While the focus of this paper has been short distance trips, it can handle longer journeys by splitting the total journey into shorter stretches and optimising each of them separately. Situations where larger corrections to the routes are possible, e.g. a route in sheltered versus a route in open waters, can be handled in a analogous manner, i.e. optimising each option individually and choosing the best of the resulting optimised suggestions.

The presented approach is highly flexible in terms of how the estimates for the energy consumption of the different phases of the journey or the entire journey are obtained. For instance, the data-based approach used for this work can easily be replaced or used in combination with simulation-based estimates based on hydrodynamic models. By using a hydrodynamic model in combination with a data-driven model, one can exploit well-known relationships from the hydrodynamic models and unknown effects that can be revealed by the data-driven method using historical data. Combining known hydrodynamic relationships can also mitigate some shortcomings of purely data-driven approaches, such as sensitivity to poor quality data and spurious correlations that do not represent physically meaningful relations.

This work has focused on the most energy demanding part of the trip, namely the transit phase, but future work will encompass the acceleration and retardation phases as well. Optimising acceleration and retardation will impact the stretch of the journey spent in transit. As seen in the demonstration section, the distance covered during transit impacts the energy consumption during this phase significantly. Hence, it has to be expected that the tendencies seen in the optimised routes presented in this paper (speed profiles and route) need to be re-examined upon the introduction of acceleration and retardation. Other factors that are known to impact energy consumption that are not considered at this point, but we plan to introduce in future version of the presented method encompass draught and trim.

Passenger comfort is an important factor for car ferries, and other vessel types, and often the main limiting factor when departures are cancelled. Perceived comfort is mainly related to vessel motion, e.g. roll, which is in turn a response of the vessel to the environmental forces to which it subjected. Future research will investigate how to incorporate this aspect into our system. Possible solutions include adding additional constraints, i.e. setting limits to the allowed vessel motion, or introducing a separate objective function on vessel motion, turning the problem in to a multi-objective optimisation problem.

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Data in Shipyards and Vessel Operations

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Abstract

This paper explores how data and connectivity underpin the entire marine lifecycle, from design through to operations. By collecting it, connecting it and ensuring it is no longer siloed, data can be the basis for true business agility within the marine industry. Layering this with holistic information management and data visualization enable a real-time view of projects, yards and/or vessels, generating potential for simplified handover, increased sustainability, alternative revenue streams, and a significantly improved ability to 'flex' business operations.

1. Introduction

Industry is at the verge of a significant new phase of productivity where the principles of data management, telemetry, automation and AI will fuse to provide unparalleled levels of human and machine insight and a subsequent acceleration of automation of processes both businesses, and in physical operations.

This potential has been coined Industry 4.0 or the 4th industrial revolution way back in 2012. Back then, many industries saw the potential of the rapidly commoditizing technology of cloud, AI, IoT and XR and set in motion various programmes of digital transformation. Whilst there are a few good examples of how effective digital transformation can be (NETFLIX), there are more examples of digital first companies such as Uber, Spotify, Amazon, suggesting that traditional industries still struggle to get to grips with the principles and are yet to deliver on the promised value of Industry 4.0.

Our experience at AVEVA has shown that this slow progress is due to many factors, for example resistance to change (especially in safety orientated industries), organisational culture, IT concerns, security concerns and in many cases lack of the right foundations for digital transformation.

Previous phases of industry revolution have focused on first establishing new building blocks for productivity and then moved on to implementation of them in new processes and working methods. For example, preindustrial revolution focused on the mass production of coal and steel, and only then the implementation of those raw sources in factories and mass production and transport. Mastering this change to first develop new blocks, and then build on those is our constant challenge.

We are now leaving the first phase of digital transformation that is beginning to generate masses of information and data and we move forward now into a phase of implementing this information to drive automation and efficiencies.

This transformation is being felt across the marine industry , from shipyards who are using digital twins to optimize their designs, production and minimize down time, and of course the shipping industry which is undergoing transformation of operational processes, as well as the fundamental building blocks such as fuel for propulsion shifting to reach aggressive industry emissions goals.

This paper looks at the fundamental building blocks of large-scale digital transformation in the marine industries, and how data platforms that can bridge the silos of both reference information and time series data will be the key to further efficiencies through collaborative working and be the basis of a machine learning and the AI driven age of automation.

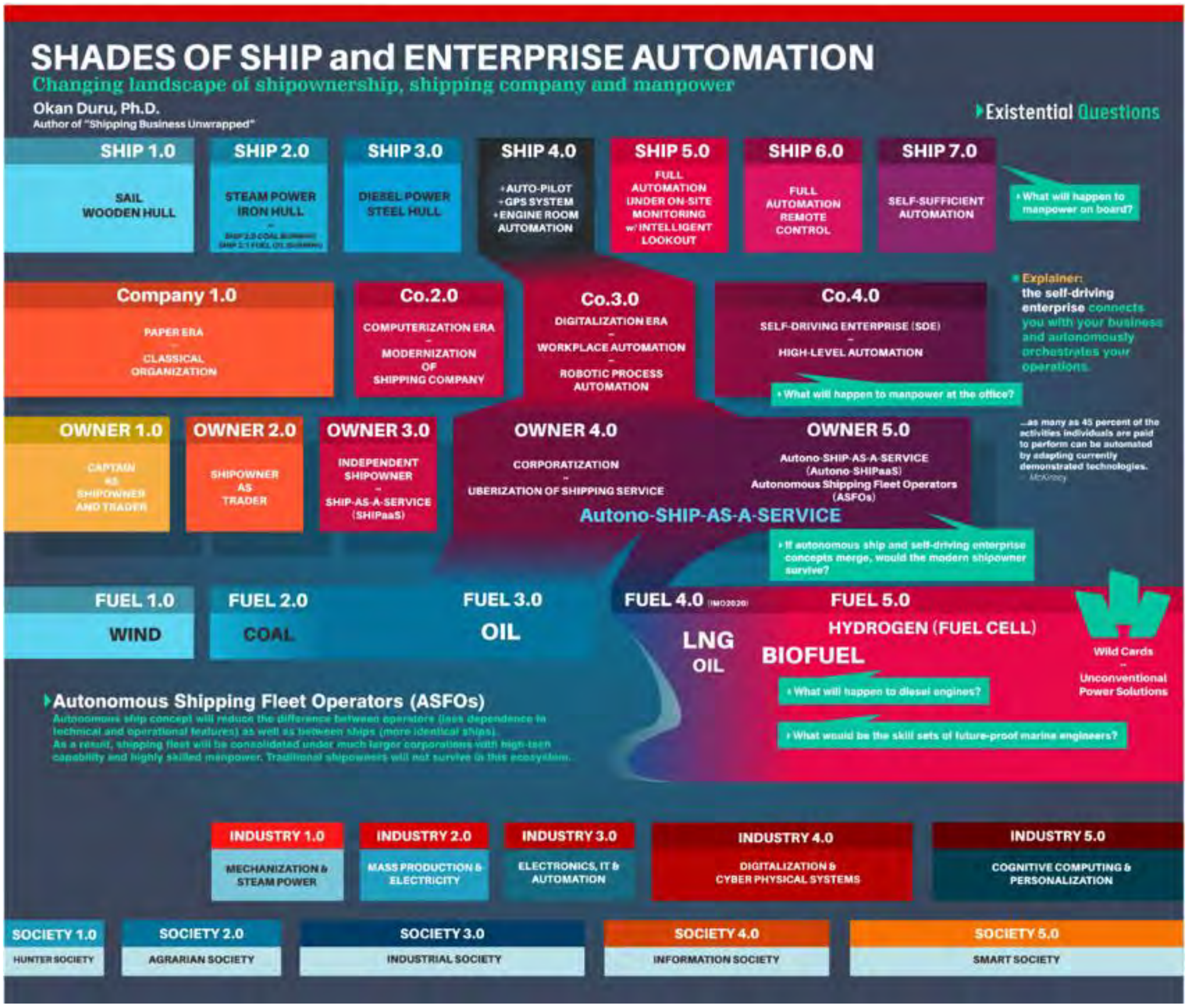

Fig.1: Diagram from Dr. O. Duru http://www.okanduru.com/ showing the evolving phases of shipping and how they are built on the building blocks of fuel and digitisation

2. Current Situation

As we leave the first phase of the digital industrial revolution, we have many of the major processes involved in the maritime lifecycle, have undergone digitalisation so that they are partially or wholly covered by best of breed enterprise applications.

2.1. Vertical Process Based Applications

In the shipbuilding industry that means for the design process we have the vertical digitally supported processes of design - Computer Aided Design (CAD) software, Enterprise Resource Management (ERP) for procurement and planning, and the production processes relies on Manufacturing Execution Systems (MES) to drive automated robotic production lines.

In ship operations we have Computerised Maintenance Management Systems (CMMS) for the maintenance on board and ERP and Enterprise Asset Management (EAM) systems covering most of the procurement and financial processes on shore, and perhaps also vertical crew management, loading software and voyage management systems (VMS).

These best of breed, or home-made applications have done much to digitalise many of the processes in our industries today. This begun with the digitisation of many of the paper deliverables that were typically associated with any given process, i.e. a paper purchase order turned into a digital one, with the benefits of more control and easier distribution. Some processes benefitted from integration across processes for example the design bill of material being connected to the material management system, and some processes changed paradigm all together to benefit from greater efficiencies, i.e. 2D drafting on paper turned into 2D electronic drafting and then into 3D modelling.

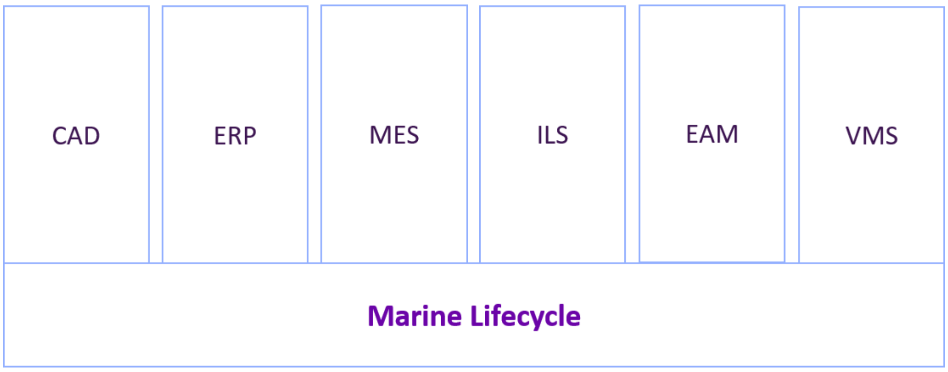

Fig.2: The vertical process centric applications most commonly used in the marine lifecycle

Today we are reaching the limits of the benefits this best of breed, vertically siloed approach can deliver as we end up with data silos as shown in figure xx above and the associated challenge to make sense of the holistic dataset across the increasing stakeholders who need to access or deliver into these silos. In our experience with very large shipyards the management of data and deliverables from suppliers rated number one on their main targets for further digitalisation.

2.2. Operational Data Silos

When it comes to realtime or time-series data from the operational phase of a assets lifecycle a similar effect has occurred. In the last few decades sensors and the infrastructure to centralise and exploit data from them, often referred to as the industrial Internet of things (IIoT) has become significantly more accessible. This in turn has led, the shipping industry, even when there are obvious challenges of remoteness and connectivity, to implement various forms of data monitoring, gathering and analysis.

Today the most common form of data collection on board vessels is still manual via processes like the noon report and emails but there are many instances of automated data gathering, primarily from the equipment manufacturers themselves where the high value of a single piece of equipment (Main engine for example) meant that collecting data to do condition monitoring was an obvious thing to do to prevent costly failures. More recently maritime start ups have become interested in the data they can collect from vessels to create machine learning algorithms to improve voyage planning and optimization, fuel consumption etc. In some cases, maritime start-ups are also installing so called IoT boxes to gather data from vessels more frequently and reliably than the noon report.

As each manufacturer, and more recently various digital start-ups deploy their own IIoT infrastructure we quickly get into the situation where there are operational data silos, and hardware redundancy onboard and on shore.

This redundancy and siloed information create new challenges for the ship operator or owner who ultimately only want to benefit from the insights that data delivers, i.e. speed up in 2 hours from now to save x% fuel. So just as vertically siloed business applications are reaching their limits in terms of improving overall productivity so is the siloed approach to operational data moreover this approach is inflexible as changes to source systems or applications makes are costly to integrate.

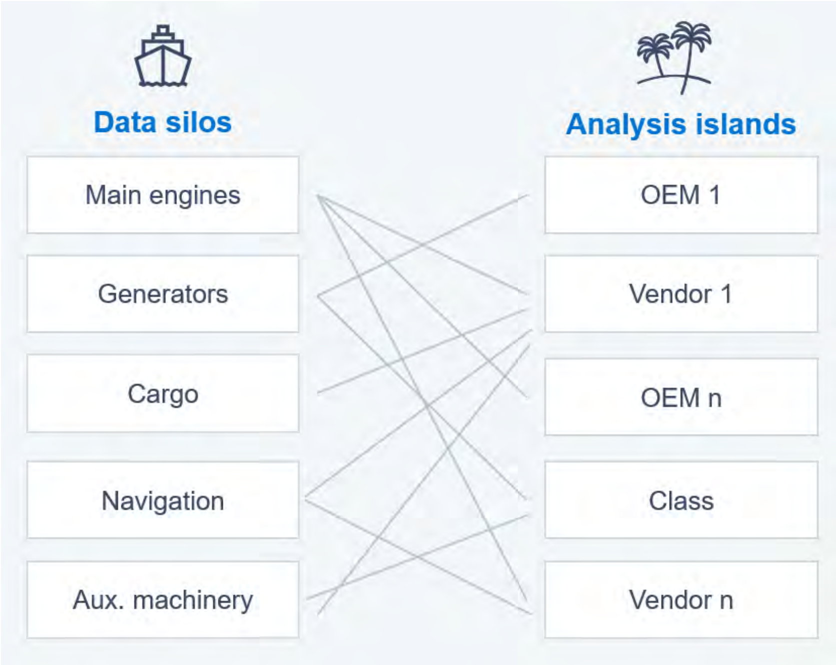

Fig.3: Equipment commonly generating data on board vessels today and the consumers of it.

2.3. The Potential of the Age of Automation

Today we are entering into the age of automation where there is an expectation that we can automate not only the mundane repetitive tasks typically found on the production line, but also more complex work such as, assembling a ship, flying an aircraft or piloting a ship.

Today's automation relies on control loops to feed sensor data to control software which in turn is programmed to actuate valves or motors to meet a desired outcome. This combination of sensors and several layers of control software can be used to automate complex movements and continuous processes for example assembly of automotive parts in a control car factory floor, control of chemical processes such as an oil refinery or chemical plant or even when combined with the all-powerful computer vision sensor of the camera + Machine Learning, the autonomous navigation of a car around a track.

When combined with data from other external systems and a reference framework we can take automation to higher levels. Take the example of the autonomous car – today the sensor site and control software alone provide sufficient information to navigate a car around a closed track or even a small town without hitting any objects and possibly adhering to the traffic signs and road markings in place. However, when combined with a detailed mapping framework (e.g. google maps), route planning software and an app that allows customer booking and scheduling of rides and an automated maintenance system we could build a fully autonomous taxi service.

The software applications associated with the business execution in shipbuilding and shipping (CAD, MES, EAM, ERP etc) are primarily based on digitised processes and workflows. Humans execute much of the thinking and problem solving based on the information they can gather or sense from those systems and the world around them.

The future of further automation of more general business processes is to use data to drive better decision making and ultimately autonomous decision making. Therefore sensing (instrumentation), data harvesting and the algorithms that can take decision based on that data are key building blocks to build large scale automation of business processes.

3. The Core Building Blocks for Digital Transformation

Digital Transformations are only possible when several key elements come together. Organisational culture and a clear vision are prerequisites to any major change but so are some fundamental underlying building blocks that can be combined in different ways to achieve almost any kind of business model or operational transformation.

3.1. Open architecture to unblock bottlenecks.

As indicated at the beginning of this chapter the marine industry has many digital but vertically siloed processes applications, and in the operational phase of the lifecycle as realtime operational data gathering and management is establishing itself we are seeing new data silos being created. Getting data out of those silos is going to be critical to ensure that further optimizations and digital transformation of businesses can be achieved. A foundation of complete and connected information is needed before any major automation can be deployed at a wide scale. Developing automated processes on poor quality or incomplete data will result in false positive or even productivity declines.

Exposing those vertical digital processes and the applications that support them into platforms where the data can flow between processes and more importantly be blended with other intersecting platform capabilities is key to the establishment of a truly digital business. Flattening vertical applications onto platforms also allows process centric applications to evolve into data centric applications with the associated automation that comes from moving to data centric. See Appendix 1- Digital Business Platforms.

Fortunately, recent moves towards cloud native computing or simply web-based applications have resulted in a great unbundling of the enterprise software space. As enterprise software companies move their traditionally on-premise server-side software to public cloud servers the benefits of interoperability between systems, often competing or overlapping, has been hard to challenge, and a great opening up of the enterprise software space is happening powered by Restful APIs and web services.

3.2. Information Backbone - unlocking data from documents

Digital processes like those handled in a CAD, ERP or EAM system consume and generate data, usually in the form of deliverables that are sent to individuals to process. For example, the general arrangement plan which is created by Naval Architects in the conceptual design phase and sent to classification societies for approval. The deliverable, in this case a drawing contains a huge amount of data which can in this case most easily be read by a human.

For that information to become more widely available and useful to other processes and ultimately algorithms, the data needs to be extracted from the deliverable and understood in the context of the process that created and consumes it. An information backbone of common data environment is typically implemented to do that where in a series of automated processes data is extracted, contextualised and presented in a way that exposes the information in a more useful way to any process or user.

Historically these processes to extract, contextualise and visualise data have been rule based or scripted, requiring significant set up and iteration to get right, especially when a new process or tool is added into the mix but ultimately working well when the structure of the data is well known and published. Today the best practice is to combine this structured data processing with machine learning to make further sense of unstructured data or information locked in deliverables that can only be interpreted by the human eye. For example, objects in video footage, photographs and even 3D models can now be automatically classified, tagged and extracted into the information backbone.

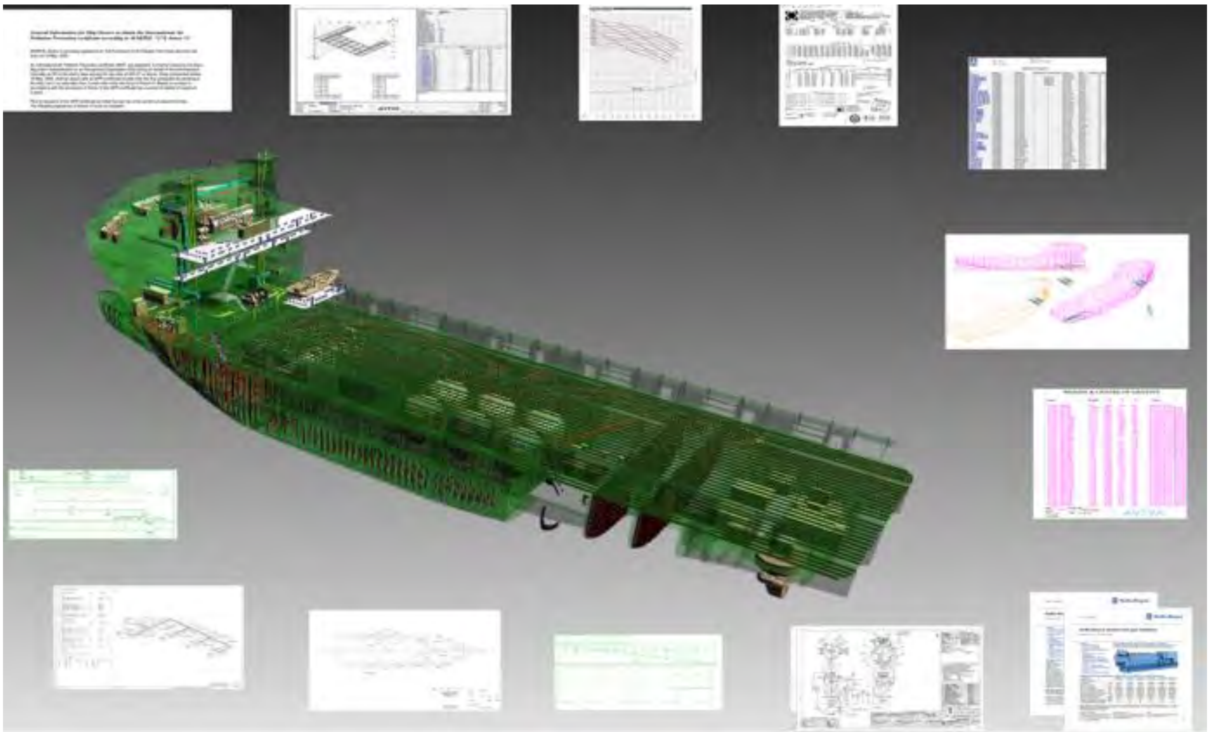

Fig.4: The combination of reference documentation and intelligent 3D product model make up most of the information backbone.

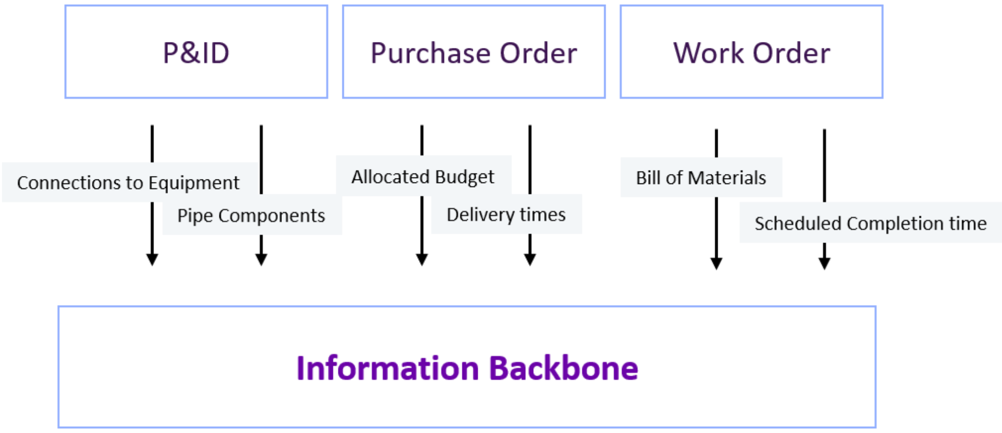

Fig.5: Extraction of structured data from documents is a key part of an information backbone

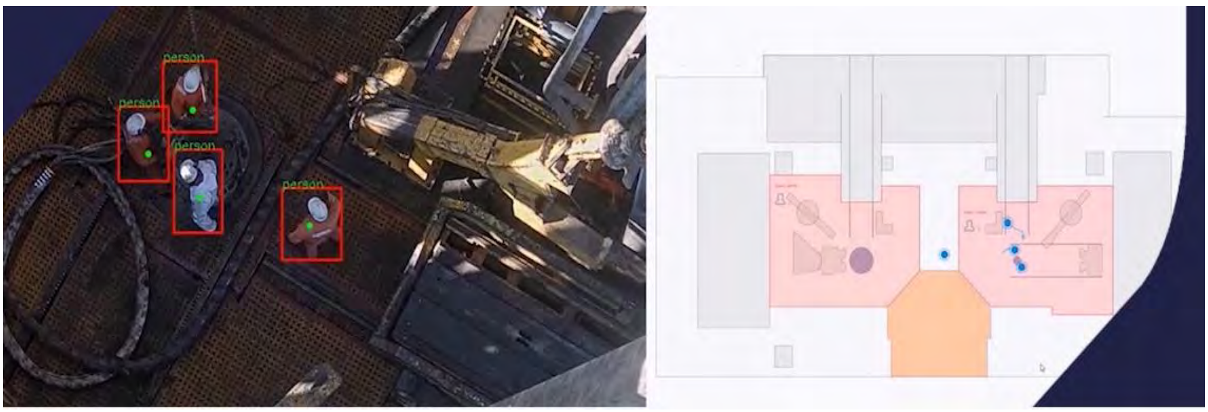

Fig.6: Machine Learning based recognition of people in hazardous areas, courtesy of Helin Data and Maersk Drilling.

The current generation of information backbones have moved to a data lake architecture where the latest cloud native databases (no SQL) technology makes sifting through very large amounts of data easy, and performant and graph database technology makes navigating and discovering unknown unknowns a visual and intuitive experience. Moreover, data lakes have an architecture that is suitable for both transactional deliverable based information and time series information.

3.3. Operational Data Management – Capture what is really happening

At the heart of operational data is the ability to connect to devices and applications and record data from them. A data historian is typically employed to capture and manage time series data for a single equipment, production line or even a complete vessel.

Historians are already embedded in much of today's shipbuilding and ship operation equipment but at the level of monitoring and or supervisory control. As mentioned in previous chapters this creates operational data silos and fails to provide an overarching view of data.

Enterprise operational data management is the application of technology like data historians but in an infrastructure that can easily be scaled to the enterprise. So instead of collecting and analysing time series data for one equipment, or one major asset such as a vessel the infrastructure is extended to collect information from all the assets in an enterprise and moreover to contextualise that data. This requires a very efficient infrastructure to allow collection of potentially billions of data points to manage the quality and status of this data so that it can be served up instantly to provide insights.

A common misconception is that historians are only made to collect data from hardware sensors for example a pressure or temperature sensor. However, time series data can be considered more widely in the context of the enterprise and used to store and analyse any events happening over a time period. For example, the quality of production work over a given time period, the productivity of the design team over a given time period, or for a specific project.

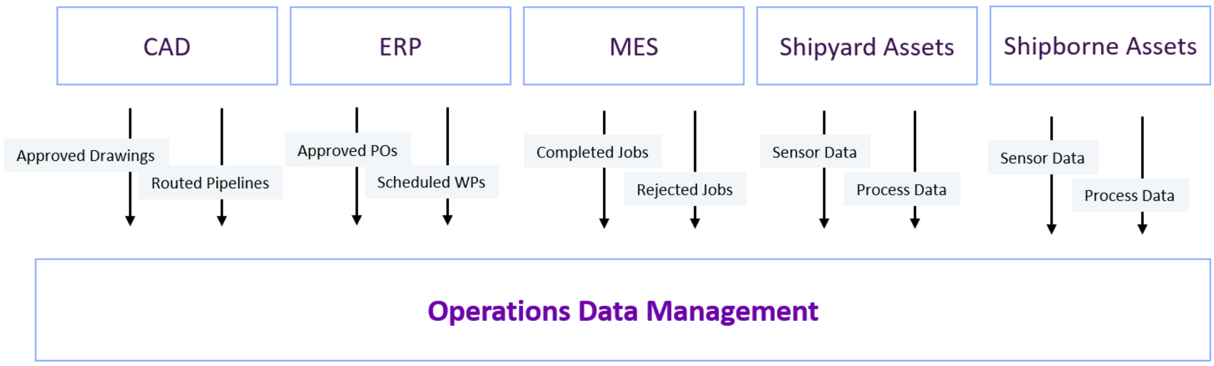

Fig.7: The Convergence of IT and OT to instrument the business processes of marine industries.

3.4. Composite Digital Thread

The combination of data extrapolated from deliverables and business processes and data directly measured from an asset or a process represents as close as we can get today to a full picture of an organisations work and current status. It is therefore the ideal basis to build models and new processes on. This is the holy grail for data scientists and machine learning experts and is indeed the basis of the various forms of Digital Twin that can be created by a business to answer key questions it may have.

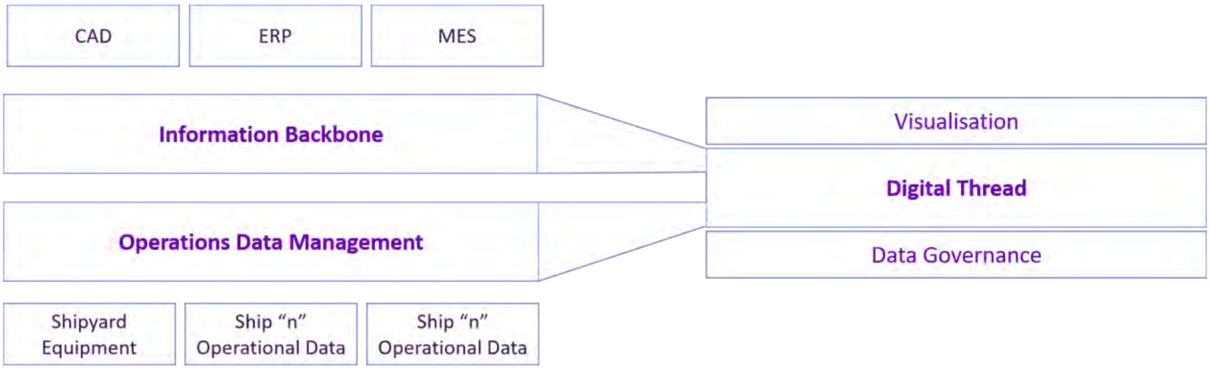

Fig.8: Bringing together relatively static data from an information backbone with rapidly changing data from Operations into a composite digital thread is key to developing a basis for further automation of processes both in the ship design process and in ship operations.

3.5 Enterprise Data Management

Bringing the transactional process driven data in the information backbone together with the Operational data management today requires traversing many different applications information Technology (IT) and Operational Technology (OT) so as a very minimum a common data model or taxonomy is needed. Typically, when building a comprehensive digital thread there are several data models to build, map to each other and more importantly maintain. A dedicated software is needed to manage and maintain this, especially as the data models, allowable associations and linkages are likely to evolve over the lifecycle of major assets like vessels and shipyards.

Gathering the data, connecting it in a meaningful way is just the beginning of creating a trustworthy digital thread the data and the connections themselves need to be governed by information standards to be able to understand and eventually assure the quality of it.

Data governance can be applied at the point of creation of data, i.e. does this object have all the required attributes, does the name contain alphanumeric characters etc. it can also be applied at the point where associations and connections are made, or even at the point of consumption, either visually via the user interface or at the point of reporting.

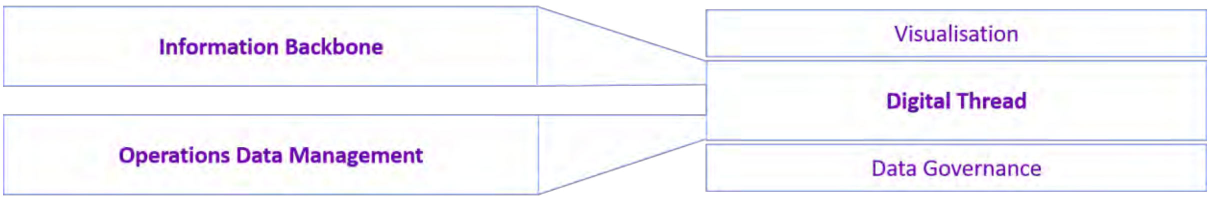

Fig.9: Layering data governance to ensure high quality data , and enterprise visualisation to ensure information consumers can access the data in the most intuitive way are key additions to the core thread.

3.6. Common Visualisation Platform

As the Digital Thread will become the basis of many working procedures and activities a common overarching approach to visualisation is needed. Visualization of information on the thread must be multi model and available on any device today.

Today visualisation technology is generally categorised into visualisation of data and visualisation of 3D and increasingly a combination of the two in a single multi-dimensional space. To this end Game Engines are one of the most promising visualisation technologies used today in the context of a digital thread. Game engines can support visualisation of interactive physics-based 3D visualisations and increasingly support advanced 2D visualisations. Moreover, game engines can today be used to create stand alone applications for all major computing platforms. However, todays most well-known commercially available game engines (Unreal and Unity) fall short in one critical area, their lack of direct connectivity to the data in the digital thread. Instead rely on copies of data from the core configured data or at best linked copies.

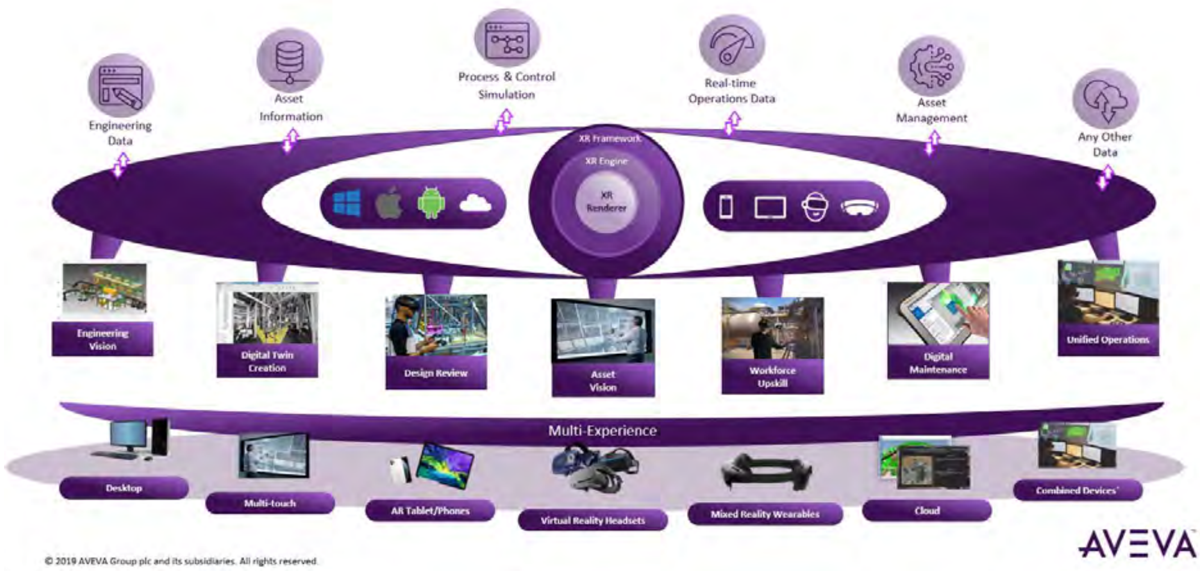

Fig.10: A visualisation platform that is integrated with the digital thread ensures that any data be that 2D or 3D visualised in a desktop, mobile or XR application can be trusted and its status referenced at any time.

4. Building on the Blocks - Building a Marine Industry with more Business Resilience and Agility

The marine industries are known for their tight commercial margins and when market conditions suddenly change history has shown that many organisations are unprepared for their new reality and fail to react in a way that ensures revenue streams are maintained yet alone built upon. This results in consolidation and a stifling of innovation. For the industry to thrive marine enterprises need to develop higher resilience to change and the agility to adapt what they do and how they do it.

Choosing the right digital transformation initiatives is key to avoid over investment and to derive rapid value, and the subsequent investment in further transformational initiatives. Today across shipbuilding and ship operations the key challenge is lack of data. Without data it becomes difficult to pinpoint where value is being lost so this is the logical starting point. When an enterprise has good quality data it is then possible to determine what to do and moreover it is increasingly feasible to use the data to build solutions to the problems. And as a business evolves from one business model to the next the data set will only grow in such a way to provide a good basis for business to have more confidence in making changes to the products they produce or the fundamental ways they generate revenue. To do this successfully, two major factors need to be considered.

4.1. Lowering the Cost of curiosity – from reporting to instrumentation

The business of building and running large ocean-going vessels is complex and has developed over many years, so you would think that shipbuilders know very well what they do and how they do it. However, time and time again when one enters the companies executing this work in a consultative role, one hears the familiar expressions, ‘I’m not sure why we do it this way but it works’, or even just ‘this is always how we have done it’. This is because in large organisations with complex processes the knowhow gets baked into the people who work there, and the business processes are not exposed or documented as that is usually just overhead. This also means that the processes are very difficult to change or transform.

Today the only way to give management visibility of what is happening in those processes is to generate reports. In the execution of shipbuilding projects reports are generated at a weekly or sometimes daily pace, usually measuring key performance indicators such as progress against a project plan in terms of drawings delivered, pipelines routed, or assemblies assembled. Clearly manual reporting is time consuming, prone to human error and a necessary overhead.

To reduce the cost of curiosity, the paradigm of reporting needs to change to a paradigm of instrumentation of business processes, so instead of manually (usually reporting scripts are used) searching the CAD/ERP/EAM databases for certain KPIs the KPI related data is automatically sensed and recorded in the operational data management backbone in a fully automatic process. As this approach in the long term will eliminate any overhead associated with reporting more data can be extracted and exposed, allowing for the creation of a foundation for data driven processes.

Fig.11: The Microsoft Azure Cognitive Services demo project the JFK files is an excellent example of using AI to traverse unstructured data in document and photo form and to turn it into structured searchable information. https://www.microsoft.com/en-us/ai/ai-lab-jfk-files

In the operation of vessels key performance indicators are reported on at a more sedate pace, usually in the form of the Noon report, which is in turn emailed to shore and transcribed to analytics databases. Unlike reporting from a business process the noon report is not considered an overhead, instead it's an essential part of the operations process providing feedback to shore based operations on the day to day running of the vessel (and hasn't changed or hundreds of years). It is of course highly prone to manipulation; human error and its frequency of reporting is very low.

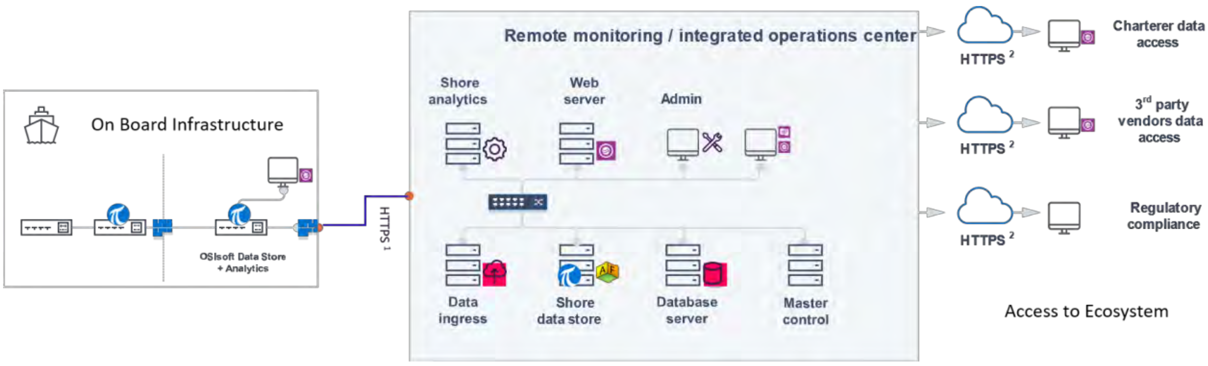

Fig.12: Typical ship to shore architecture for fleet remote monitoring

Today the infrastructure to sense data, collect it and contextualise operational data can be installed on very small, low-cost edge computing devices, this data can in turn be compressed, sent back to shore via sat comms where larger operational data management set up can be use to connect it to other data in the enterprise and make it available for further analysis.

Today it is easier and more affordable than ever to instrument both business processes and operational assets, and the technology exists and accessible enough that any user in an enterprise should be able to satisfy their curiosity for information. This is the first major building block to large scale digital transformation.

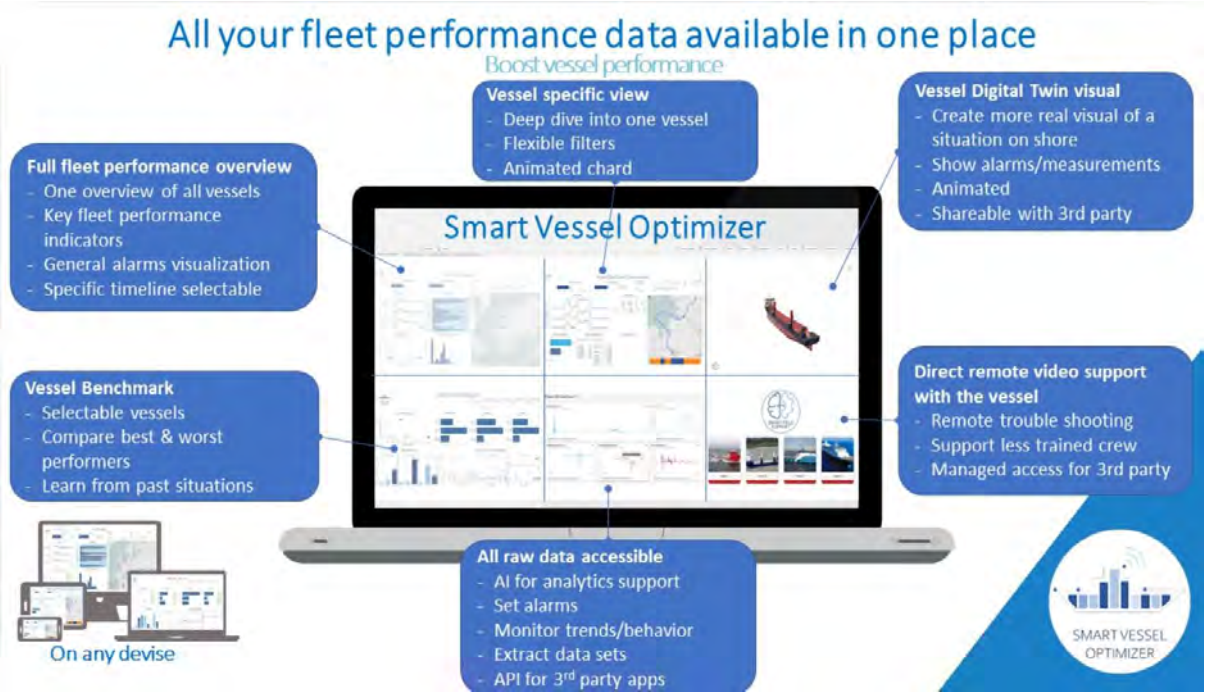

Fig.13: An example of modern operational data visualisation combining realtime data from sensors with operational process data, all possible after installing a single IoT box from the Marine Start up Tech Binder.

4.2. Data Driven Processes – major step forward for general automation

With a composite digital thread in place that understands workflows of processes and that instruments the KPIs of those processes, new data driven processes can be developed in an organisation.

Moreover, the level that processes, tasks and assets are instrumented at, directly relates to how much benefit can be derived, ether through better insight into what is happening or via automation of processes and tasks. For example, at a very low level, if the design process and tools are instrumented to the level of collecting mouse clicks and keyboard entries the data that is generated can be used to automate or predict certain repetitive tasks.

A level up form this the instrumentation of design decisions connected to historical operational performance logs will lead us to a data driven design approach whereby ship designers can make better use of historical data to optimize designs for sisterships and even first of a kind. Today Naval Architects look back at previous projects as a basis for their new designs but with a full history of design projects, design decisions made and the impact on operational performance of these vessels available the guess work will be taken out of optimization of designs and in significantly less time. Today this is still in the realms of dreams as no such complete data set has been captured or understood. Instead, we can only generate the fundamentals of a design from data, such as a layout or perhaps a power train configuration.

Data Driven Operations and Maintenance on the other hand have already made great leaps forward with firstly condition based maintenance based on actual sensed condition of bearings or other critical parts and more recently predictive maintenance where algorithms are able to give early warnings of failures based on anomalous data when compared to the standard parameters of operation. Today these forms of data driven operations are mostly executed by equipment manufacturers and sold as value added digital services leaving the Owner /Operators (OOs) of vessels with no data of their own. However, as OOs are now driven to transform their businesses to operate in more sustainable and transparent ways the paradigm shift to data driven operations is happening rapidly.

4.3. New business processes and services

Ultimately businesses who can weave the composite digital thread of IT and OT information together will have the basis for building completely new operational models. Already we are seeing the shift towards digital twin centric business for shipbuilders and designers whereby smaller design agencies want a digital vehicle to deliver their design services to their clients without the hassle of delivering documents or even file servers of Navisworks files, they want a seamless delivery of the engineering twin they create as they create it. And large shipyards have this digital handover coming weather they like it or not, already in larger contracts a digital handover is expected if not particularly well defined, and we already see the first mandated deliveries of digital twins often be that in the form of laser scans or photogrammetry but we also soon expect to see more mandated handovers of subsets of the design data.

Recently industry consolidation has allowed large enterprises to form in the marine space with a good vertical coverage of the whole value chain of the main industry, for example Mitsui industries in Japan, or Kongsberg Maritime are groups with marine equipment manufacturing, shipbuilding and ship operations divisions. These companies most likely still run siloed business processes for each of their divisions but are in a great position to deliver IoT ready vessels with a full monitoring and asset management service to their clients. Combining operational data insights form their machinery to a) improve the reliability of their equipment and b) to provide operational feedback form the holistic operation of their vessels to improve sister ships and variants of the original design.

5. Summary

Historical implementation of technology has led us to a point where applying the same deliverable/ process centric approach to digitalisation will not yield transformative improvements, as the individual processes become optimized but the overall process optimization or indeed automation stay elusive.

Today organisations see the potential of a data driven Digital Transformation and are seeking to highlight and weave together the digital threads that exist in an organisation today. Finding those threads yet alone maintaining their integrity and connectivity is a major challenge today as information is locked up in proprietary platforms, databases or even documents. An information backbone, or common data environment approach is essential for an organisation to be able to say what information relates to what product and to be able to trace why a certain decision was made. Information backbones can be created and maintained in-house, but a commercially available solution allows an organisation to benefit from an all-encompassing approach where data is collected from the data source directly or scraped from documents and images with the latest machine learning techniques. AVEVA'S experience in the oil and gas industry has allowed us to develop not only a robust solution but the consultancy services that are often needed to put in place information standards and contracts between those generating the data and those who need to consume high quality data in the products lifecycle. As the importance of digitalisation in the marine industry grows, we see the demand for creating an information backbone that bridges the newbuild phase and the operational phase increasing and it seems inevitable that the marine industry will learn from the lessons in the energy sectors where handover of a configured digital asset is mandated into most Engineering Procurement and Construction contracts today.

However, an information backbone is not enough to deliver truly transformational change to an organisation, the way forward is to instrument both the business processes and the operational assets, a process that is now both affordable and scalable thanks to Enterprise Operational Data management platforms like the PI system. These systems will collect the data that is the real earth, from which the new oil will be discovered through enterprise visualisation technology and machine learning.

And when combined together into a composite digital thread, organisations will be able to tune business processes according to the instruments they put on their business not only asynchronous reports, and ultimately be able to automate many of the processes they thought were too complex to automate.

References

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Appendix 1 - Digital Business Platforms

According to Gartner business who want to take advantage of digital business models need a combination of platforms, depending on what their business objectives are. Digital Platforms suggest that unbundling vertical applications and the data associated with them allows better integration with other forms of platform as indicated in the diagram below. The diagram also highlights the importance of a data and analytics platform that reaches into all aspects of a business and through machine learning and Artificial Intelligence delivers value back into each part of the business. The full landscape of platform looks like Fig.14.

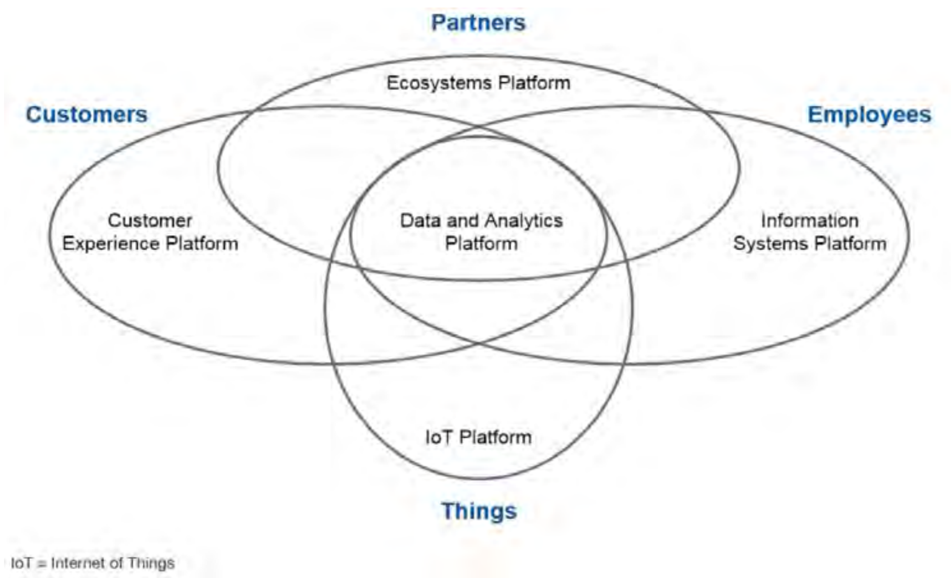


Fig.14: The digital business technology platform

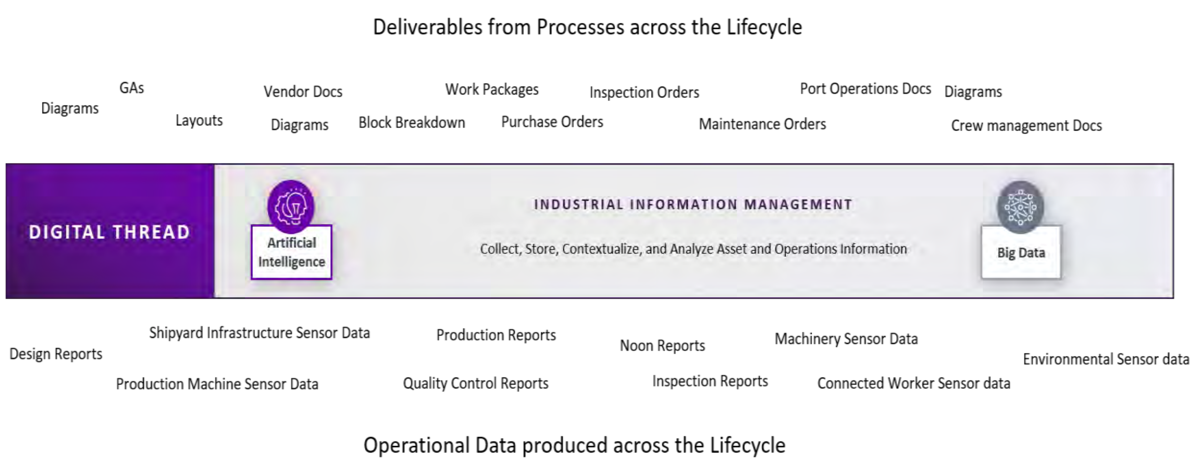
- Information Systems
  Today most of the applications and information technology and communications (ITC) technology deployed in shipyard and onboard vessels are in the information systems region of the above diagram, e.g. CAD; ERP, PLM, MES, CMMS, e-mail i.e. the tools that directly serve the employees. There may be localised integration, for example between CAD and ERP usually point to point via a custom middleware. Ideally a platform would be made available to support the integration of work process across the business here, with centralised workflows and definition of object classes and relationships and a repository or federation of the data in the master systems of CAD/ERP/etc. Today most vertical applications are micro platforms in their own right and exist primarily as on-premise enterprise managed applications. To make the maximum benefits of the platform approach an unbundling to a cloud-based architecture is necessary as interfaces, user experience and security access can be unified.

- Ecosystems
  As the shipyards increasingly practice the outsourcing model, there is ever more need for the Ecosystems platform, at its most basic level this is could be access to a shared network folder or a cloud file management service, ultimately allowing controlled transfer of work to and from subcontractors and the main yard. Often this is integrated into the Information systems platform of the yard. Once again a unbundling of enterprise managed applications to a cloud based infrastructure is beneficial to enable access outside the companies firewall and truly collaborative work process with partners. And as many of the collaborative practices become purely digital services the cloud-based approach enables true sharing of value and workload. Take the 3D approval process being developed by most classification societies today where a API form the 3D CAD system to the 3D approval platform would enable very streamlined approval processes and collaboration.

- Customer Experience
  The customer experience platform is primarily targeted at business to consumer (B2C) enterprises. Where a customer portal or a website provides the main interface between customer and business. In the marine industry as companies develop new digital only services this is more likely to be a cloud-based platform resembling a store where services can be subscribed to and accessed. DNVs Veracity is an example of a customer experience platform. As shipyards strive to maintain their key customers and sell new services to them, we see a need for the Customer Experience Platform serving customers with the information they need, a combination of a services or app store front, connected to a Customer Relationship Management (CRM) system in the back end is the most likely configuration here with links to the corporate website and social media.

- IoT
  Any organisation that has physical assets will increasingly need an IoT platform. IoT platforms begin on the so called ‘edge’ where sensors and IoT devices gather data at the point of generation. As there are many standards and protocols for this edge data gateways or converters are needed to bring data into a more homogeneous state. IoT platforms usually include control mechanisms both hardware and software as mentioned above in earlier chapters. The data gathered at the edge is usually very large volume and complexity so compression techniques and data management is needed to keep the harvested data in order. IoT platforms often extend into the visualisation realm, adding on Human Machine Interfaces (HMI) at the edge and Supervisory, Control Automation and Data Acquisition interfaces in the control room.

Appendix 2 - Forms of Data in the marine industry



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