GENERATIONS

Mission Zero

Powering sustainability

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01 Framework

Committing to a sustainable future

The transition to a sustainable economy is one of the major undertakings in human history. Industrial technology companies have a critical role to play in this historic effort, applying the brightest minds to develop technologies and deliver solutions that will enable the global green shift.

Juha Koskela
Division President
ABB Marine & Ports

As a major stakeholder in this movement, ABB Marine & Ports is committed to supporting the shipping industry's decarbonization agenda with electric, digital and connected technologies that allow cleaner and more efficient operations.

Meeting the International Maritime Organization's goal of halving greenhouse gas emissions from ships by 2050 is a critical step toward sustainability, and will require a comprehensive and proactive response from the maritime community. Shipping is well positioned to take concrete action by choosing to implement technologies that provide reduced fuel consumption and lower emissions.

Realizing viable green supply chains is another key factor. Much depends on how prepared each country is to make the energy transition. The basic prerequisites include supportive regulatory frameworks, access to financial resources, and a commitment to building the necessary infrastructure. Encouragingly, we see that support for zero-emission marine technologies such as ferry electrification is growing in many parts of the world.

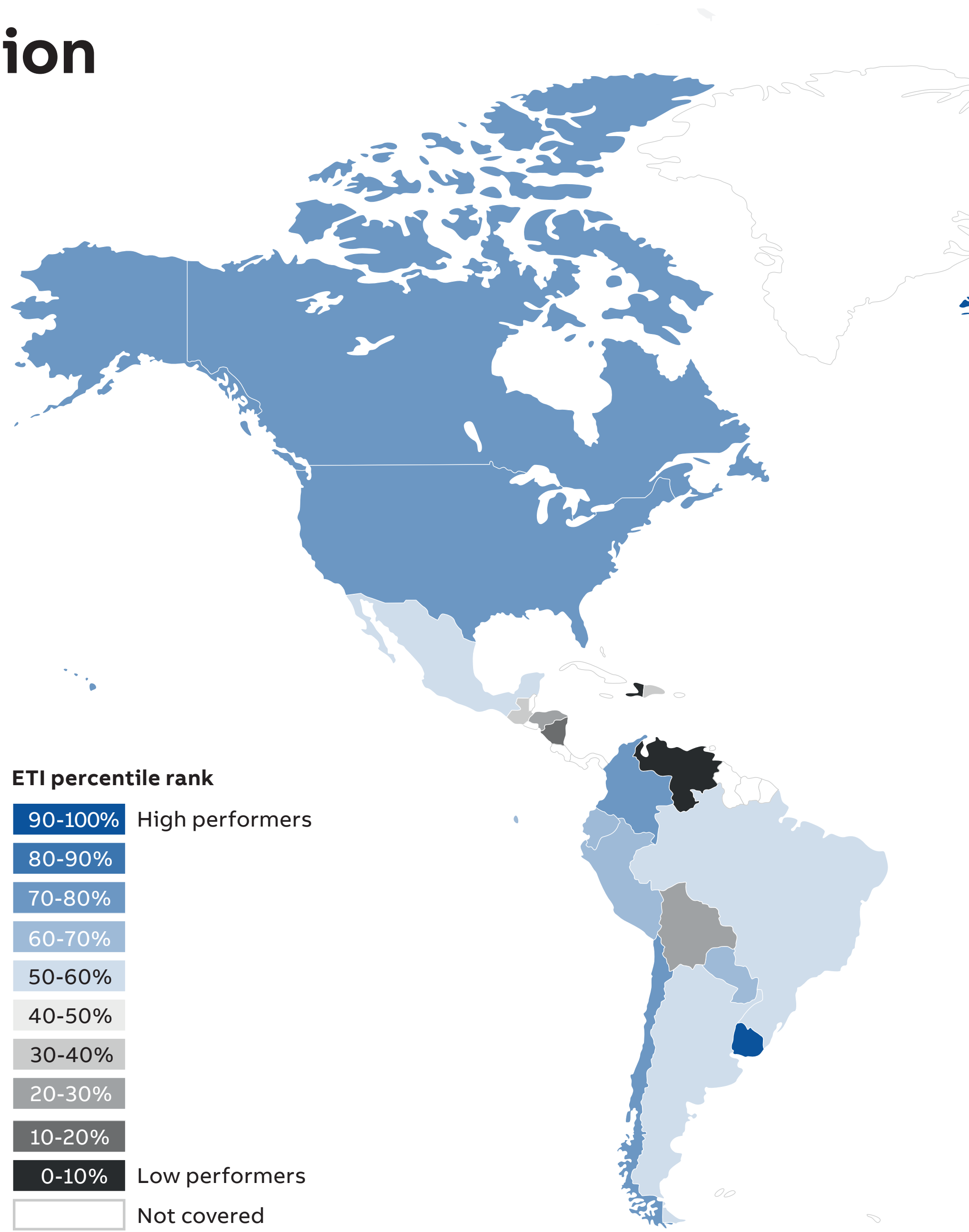
Building a future together

Regulatory pressures have helped set the green shift in motion, but sustainability is becoming steadily more critical to corporate social legitimacy. In response, stakeholders across the value chain are increasingly demanding and delivering innovative solutions with a reduced impact on the environment.

As the shipping community begins to bounce back from the disruptions of 2020, we feel certain that environmental stewardship will take an even higher place on their long-term list of priorities. We believe shipowners and suppliers across the globe will redouble efforts to comply with environmental regulations and do their part toward ensuring a sustainable future. Now more than ever, we need a collective response to our collective responsibility.

Energy transition index 2020

The Energy Transition Index (ETI) benchmarks countries on the performance of their energy system, as well as their readiness for transition to a secure, sustainable, affordable and reliable energy future. The ETI 2020 ranks countries on a scale from 0-100 percent.



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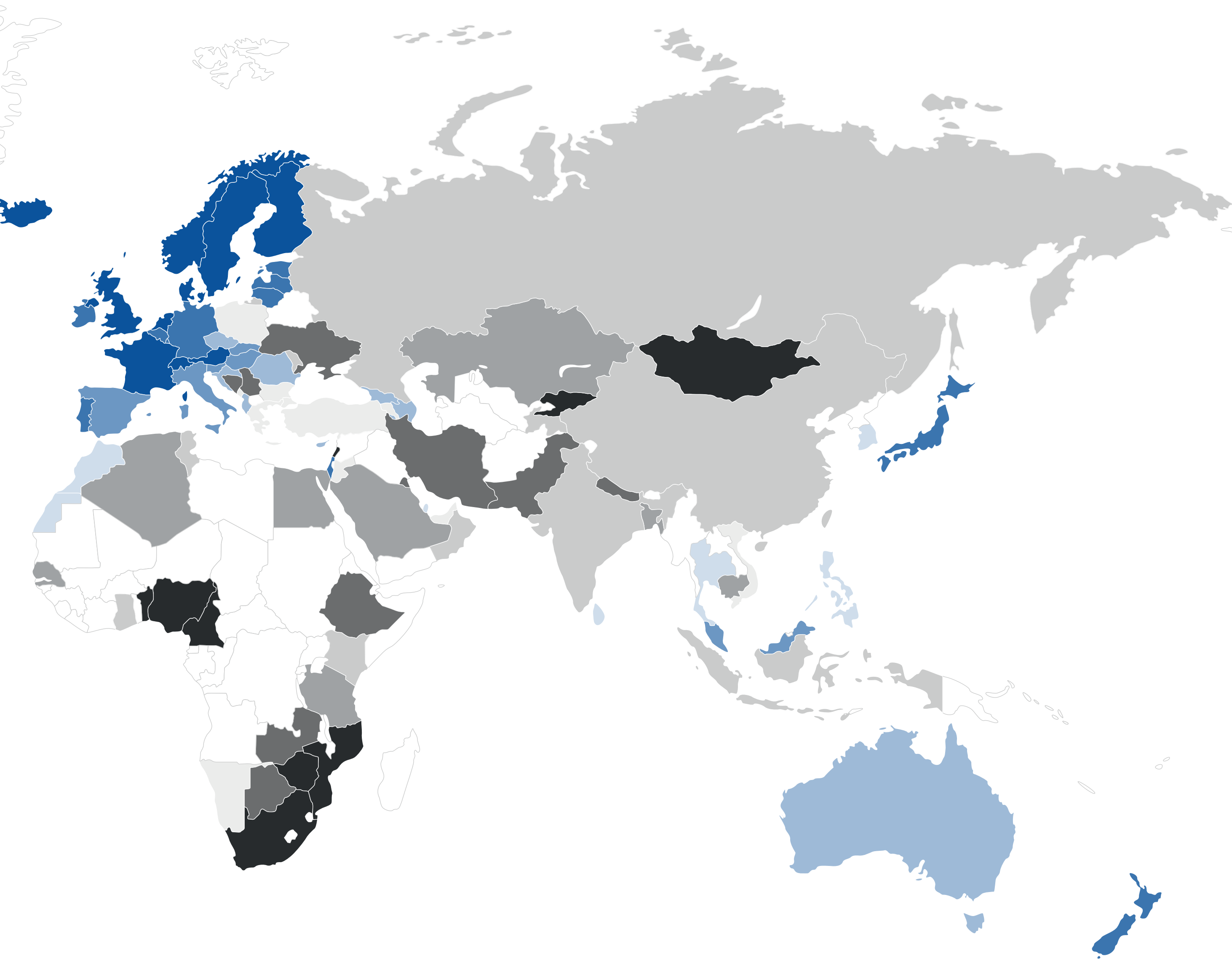
Source: World Economic Forum, Fostering Effective Energy Transition 2020



2020 and beyond
The emergence of a new era

When Sadan Kaptanoglu took the helm as president of the Baltic and International Maritime Council (BIMCO) in May of 2019, she knew full well that the shipping industry was headed into uncharted waters.

"Shipping is the first international industry to have to comply with global emissions regulations," she points out. "The first year of the International Maritime Organization's 2020 sulphur cap[1] regime will be a challenge for everybody. Shipowners, ports, charterers, flag states and class, we will all start learning from the first day."

Kaptanoglu now serves as both President and chairperson of BIMCO and Managing Director of Kaptanoglu Shipping, the family business since 1904. The list of pressing issues is long in both roles, but she is clear on her priorities: "The IMO sulphur cap 2020 is the most important issue for all of us right now. First of all, because it's good to do what we can for the environment, and every individual has a responsibility. But, of course, also in order to be compliant. We in BIMCO will work with our members to resolve compliance issues as they arise."

BIMCO is the largest of the international shipping associations, representing shipowners in 120 countries controlling around 65 percent of the world's tonnage. Kaptanoglu affirms that one of her biggest responsibilities is to maintain a level playing field for members. "Our goal is to achieve even and fair application of regulations for all, and that includes protecting the innocent. Sometimes there is a genuine commitment to comply, but things can happen that make it impossible to meet every requirement in every situation. When non-compliance is not intentional, those parties need to receive fair treatment."

Ensuring compliance is also a challenge for regulators themselves, she acknowledges. "The IMO's capacity is stretched to the limit now. In such a demanding situation it is important to maintain dialog and share experiences. We anticipate a heightened level of communication with the authorities in the coming period."

The first year of the International Maritime Organization's 2020 sulphur cap[1] regime will be a challenge for everybody.

Committed to compliance

Kaptanoglu is in no doubt of the commitment among stakeholders to comply. "Virtually everyone in the industry is well intentioned. They are making preparations according to their choices. There will be different versions of how to address things, but companies will always strive to comply."

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Sadan Kaptanoglu
President
Baltic and International Maritime Council

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[1] Regulation by the International Maritime Organization to cap the global fuel sulphur limit at 0.50 percent from January 1, 2020(http://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx)

That being said, she emphasizes that the first real test is coming now. “My advice to shipowners and others is to review everything you are doing very carefully. Be sure you have your plan for compliance in place. Things could of course change, so it is important to maintain close communication with class, flag, charterers, and everyone in the value chain.”

Though the major new regulations place a heavy burden on all, Kaptanoglu warns that shipowners cannot afford to underestimate any regulation, no matter how small. “I believe owners will comply with every regulation to the best of their ability. They know that they must comply in order to work.”

And no sooner than the 2020 sulphur cap requirements have been assimilated, the industry will have to move on to even bigger challenges: “Though it may seem disheartening, IMO 2020 will basically serve as a trial run for the bigger task ahead, that of reducing GHG emissions,” she says.

Our goal is to achieve even and fair application of regulations for all, and that includes protecting the innocent.

Seeking new solutions together
In preparation for the next big push, BIMCO has established a speed optimization group with all presidents, past and present, as members. “We have submitted a paper to the IMO suggesting limitation of ship power as a means to reduce emissions. Slow steaming has achieved good results, but when markets pick up, the demand for speed returns. In order to stop the negative effect of this, we propose to regulate the propulsion power of ships. If we want to sustain the greenhouse gas gains achieved by slow steaming, this could be a good short-term solution,” Kaptanoglu offers.

New technologies and fresh innovation will also be needed to meet future environmental requirements, she says. “BIMCO would support a fund to support research on emissions reduction technologies. Everybody is doing their own research, but we could move even faster if we worked together.”

Kaptanoglu reports that BIMCO is also reviewing different models from other organizations. “We have held roundtables with the International Chamber of Shipping, Intertanko, Intercargo and others,” she says. “We are also talking about future fuel solutions with the energy companies, some of whom are BIMCO members. Shipowners cannot bring about the necessary changes by themselves.”

The force of flexibility
BIMCO members have different ideas about how to comply, she adds, including LNG and hydrogen, as well as other fuel alternatives. “I don’t think it will be possible to find a dominant solution like HFO for the future. Maybe we will end up with three or four main options. Companies will pick their preferred solution according to trading patterns, regions, budgets, and more. It’s not like the old days when a decision was made from above and everyone followed along. One size does not fit all anymore.”

Kaptanoglu believes that the ongoing implementation of ballast water treatment regulations will also require a learning period. “Now that it is taking force we have to learn as we go. But shipowners need stability and facts to work from in order to serve their trade. I can see the frustration in the owners’ eyes when they talk about how difficult it is to find the optimal path to compliance, but we have to come out of the pain with something better.” Her advice to members is to comply first, then begin the learning process to arrive at the best solution.

“We cannot predict this future. The technologies look good, but from now on, there will always be room to improve, and always a reason to improve. The time of the 40-year technology is past. We need to be more flexible from now on, but this also means that costs will increase and be passed on to customers.”

Kaptanoglu maintains that shipowners are keeping their side of the bargain. “Now we will see if the rest of the world is really committed, and I want to believe that they are. Remember that freight is only a fraction of the end price. If you want a cleaner world, you have to be willing to pay a little more. Is everyone willing to pay for a cleaner future? This will be the test.”

An active WISTA (Women's International Shipping and Trading Association) ambassador, Kaptanoglu admits to finding it strange that diversity is not the norm in shipping, well into the 21st century. “For me and my family, this is a natural thing. Our family business is run by women and men working shoulder to shoulder,” she relates. “Perhaps we should all be a little ashamed that gender equality has not been established by now. We need to increase the number of women in shipping, and increase their contribution to the industry,” she says.

Making room for all in shipping
Though she is fully occupied with unprecedented regulatory pressures and running a business, Kaptanoglu will continue to address the persistent gender imbalance in shipping. “BIMCO is a 114-year-old organization, and I am the first woman president. That is a great honor. But a one-term woman president could still be seen as a novelty.” With the appointment of Sabrina Chao of Wah Kwong Maritime Transport Holdings Limited as BIMCO president designate, Kaptanoglu believes that BIMCO has entered a new era.

Perhaps we should all be a little ashamed that gender equality has not been established by now. We need to increase the number of women in shipping.

“It’s not that there are no qualified women in shipping. The problem has been that qualified women are often not recognized by the men in the industry, and we must strive to change this,” she says, citing the IMO’s appointment of a committee to work toward empowering women in shipping as a good example.

“Not long ago I met a woman who was technical manager in a large shipping company,” Kaptanoglu recalls. “She said it was encouraging to meet a woman BIMCO president. I replied that it was even more encouraging to meet a woman technical manager. I know this industry, and I know there are very set gender roles in shipping. If women do not see a future here, they will not join. We need to ask ourselves what we can do to convince them that they have a future in shipping.”

Finding strength in unity
Ever since her start at the helm of BIMCO, Kaptanoglu has praise for the work. “Every member has a say, and we are working even closer with other organizations to address problems. This is very important, especially in these challenging times when dialog is more important than ever. I appreciate the way BIMCO is organized and the opportunity this affords me to work closely with the other organizations and the rest of the industry,” she confirms.

“I knew I would be assuming responsibility in a difficult period for our industry, but everyone acknowledges the challenges ahead, so I don’t feel that I am facing it alone. There is a stronger feeling of unity now than ever, and I believe this will continue to grow.” From all the struggles should emerge good things, Kaptanoglu concludes: “I honestly see this as more of an opportunity than a problem, and I will do my best to accommodate the needs of our members and serve our industry during my term as president.”

There is a stronger feeling of unity now than ever, and I believe this will continue to grow.

The future regulatory landscape
Keeping pace with compliance

Environmental regulations are a positive force in driving shipping toward the green shift – and yet they are complex, with many factors to be dealt with as owners and operators strive to comply. Eero Lehtovaara, Head of Regulatory Affairs at ABB Marine & Ports, shares his views on the maritime regulatory picture.

The balance of focus between past, present and future compliance is key, Lehtovaara believes. “The attention that owners will have to pay to emissions and ballast water regulations risks eating up all their capacity to handle other, upcoming compliance issues,” he says. “Both these measures are based on decisions from many years back, but other important legislation continues to be passed and will demand attention as well.”

> The attention that owners will have to pay to emissions and ballast water regulations risks eating up all their capacity to handle other, upcoming compliance issues.

Lehtovaara adds that it is important for the industry take into consideration the time scale of 2050, when the International Maritime Organization (IMO) is calling for a 50 percent reduction in marine greenhouse gas emissions compared with 2008. “Those in power who have made the decisions will be gone long before these regulations take effect, and it is essential to prevent the regulatory environment from fragmenting before we can reach the goal.”

Progress toward the major goals will require more precise decision making at many levels, Lehtovaara maintains. He offers that a regulatory push could start with domestic traffic: “Goals must be fed by incentives, and perhaps incentives will also come from elsewhere than the IMO.” Local and regional authorities can place caps on emissions, he says, but if some are stricter than others, the risk of unclear consequences for shipowners must be dealt with: “Those who don’t comply could simply be excluded from local trade, but the responsibility could also be placed unjustly on the global foreign fleet.”

That said, Lehtovaara recognizes that compliance will always be crucial to trading. “Owners and operators must comply in order to work. This is precisely why companies are spending so much time and resources on ballast water, sulphur cap and greenhouse gas emissions compliance.” The key, he believes, will be for industry stakeholders to resolve the challenges of complying with these important regulatory milestones, while putting aside additional resources to meet future compliance demands.

Legislation and environment
Existing and known legislation

2018

Fuel oil consumption data collection system
Monitor from 1 Jan 2019
SEEMP Part II with plan

EU ship recycling
First IHM application for EU flag newbuilds

Initial GHG reduction strategy

2019

EU MRV
Monitor 2018
First reporting 2019

Bunker delivery note
Fuel sulphur

EEDI amendments
New references line for RoRo and RoPax vessels

Baltic Sea Special Area
Passenger vessels only
New 2019
Existing 2021

Ballast Water Management Convention amendments
Retrofitting schedule
Approval guidelines

2020

EEDI
Phase 2 (2020)
Phase 3 (moved to 2022 from 2025 for several ship types)
Phase 4

Annex VI – SOx
0.50% outside ECAs

2021

NOx ECAs – Baltic Sea, North Sea/ English Channel
Tier III

2022

Ballast water treatment systems
Latest retrofit deadline 2024

Ship recycling convention
Six member states 21.23%

Of particular importance

Legislation and environment
Legislation under development

2020-21

Ballast water management guidelines
Sampling & analysis
Local water beyond capability

Electronic record books
MARPOL I, II, V, VI

Arctic HFO
Ban or risk control

Carriage ban
> 0.5% suphur fuel

2022-24

Black carbon
Arctic

IMSCB code 05-19
Materials emitting flammable or toxic gas
Bauxite cargoes

IBC code
Products toxicity ratings review

Marine plastic pollution
Litter including microplastics

EGCS Guidelines review
Use > 2020
Breakdown
Sampling

Autonomous ships
(MASS)

Cold ironing in port
Safety standards

Survival craft ventilation

Of particular importance

Industrial personnel
New SOLAS chapter and code
Interim: cargo certification

Cybersecurity
ISM

CSS code
Weather dependent

IGF Code Rev.1
Fuel cells
Methanol
Ethanol

2025+

Onboard lifting appliances and winches

Polar Code – non-SOLAS ships
Safety measures

GMDSS review
SOLAS Chapter IV

Power supply availability
Passenger ships – side raking damage

IGC Code Rev.1
Liquefied hydrogen

RoRo fire safety
Deck girder sprinklers

Goal-based standards
Inc. LSA

Life-saving appliances

Mooring
3000 GT+

Defining autonomy – or not

Asked to provide his definition of autonomy, Pierre Sames, Group Technology and Research Director at DNV GL, one of the global bastions of technical knowledge, politely declines.

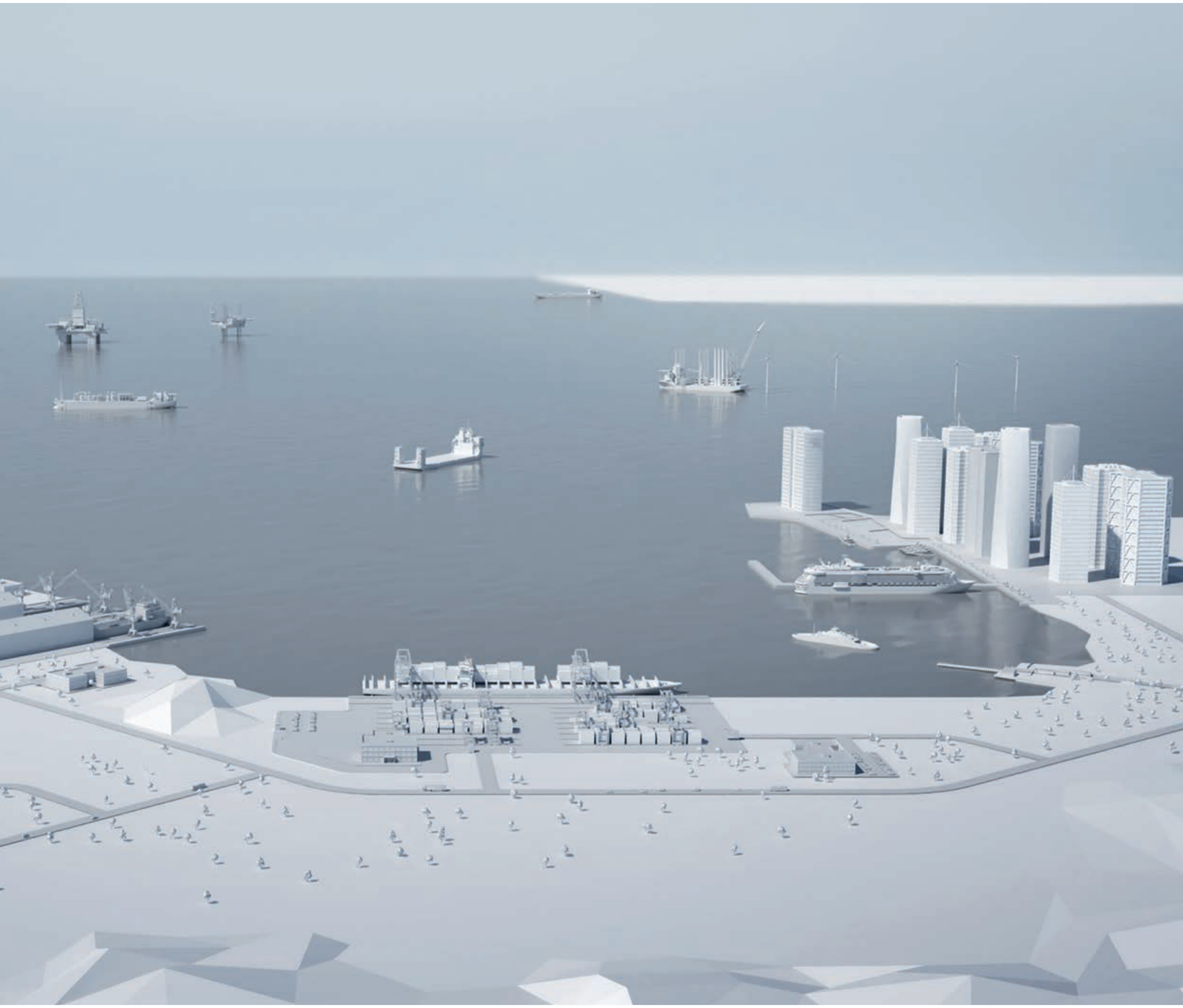
"DNV GL does not have a definition of autonomy levels," he says. "Why limit ourselves to such a definition so early in the game? Who knows what it will become?"

He tells that DNV GL, a globally leading quality assurance and risk management company, tends to look at projects first and consider elements of autonomy as needed. "A particular case may feature different combinations of technologies, from fully autonomous in one area to remote control in another. We have to look at the outcome, and a strict definition of autonomy levels would limit us."

DNV GL does not have a definition of autonomy levels.

With a PhD from Hamburg University, Sames was many years with the classification society Germanischer Lloyd, and, after the company merged with DNV, continued in DNV GL. His focus throughout has been on engineering and research management.

"Rather than defining autonomy levels, we have defined ship functions," he says. "Navigation and power or propulsion are the most likely areas of



attention now. For each you can pick different approaches: automation, remote, or autonomy." For example, he cites that conventional navigation can be combined with a fully automated engine room. "So why do we need a definition?" Besides, he jokes, "The truly autonomous ship would probably just set sail for the Caribbean."

Planning ahead, acting now

Like most in the industry, Sames believes the reality of ships making decisions without humans, at least larger ships, is a long way off. "For navigation, most ships will be on a leash, just not all the time. The ship must do what is required to remain safe, or follow pre-programmed instructions. The main requirement is to achieve minimum risk states." Short sea and shuttle ships are the more likely candidates in the near future, he says, operating in restricted areas.

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Highly automated and remotely operated ships could provide new and attractive shore-based jobs for highly qualified employees.

"For now, our aim is to help our customers sort out their ideas, to arrive at a solid concept of operations. This concept has to detail the operational scenario: where are they sailing, what is their purpose, how do they operate? What is the safety philosophy and which maintenance is required?"

Make the best of what you have

The main advice from Sames is not to take too large steps. "Use what you have. Regardless, you can only apply what has been through the process, from flag, to class, to owners and OEMs. It is essential to have processes in place to guide the progress."

Though other industries are progressing on autonomy, Sames sees no real transfer of experience taking place between the automotive and aviation industries and marine. "Navigation systems and situational awareness share some of the same technology, so we could transfer basic algorithms, but they would need to be retrained for a maritime application. And sensor packages would likely be different as well."

Machine vs. maker

One of the long-standing questions in the autonomy debate is what happens when humans meet machines. "We know how our counterparts will react, but not how a machine would. Reaction times and assumptions are not the same. It is impossible for a human to anticipate how a machine will react, and this is a major barrier to implementing autonomy in a safe way."

He refers to route exchange in shipping as one way to reduce uncertainty when two vessels interact. "The purpose is to inform surrounding vessels of your intentions. Two merchant ships will follow normal rules of engagement. When a vessel approaches from starboard, you need to go astern. We would need to ensure that autonomous ships follow the same rules as long they navigate in the same waters as conventional ships."

In such cases it would be better to have a system to guide the interaction also on conventional ships, he argues. "Combined with cameras and other sensors, this would provide a safety boost. Decision support and route exchange can then also improve the safety of the current fleet, not just in future autonomous ships."

The value of autonomy

The relative value of autonomy is also different for different ships, Sames points out. "It would have a higher impact on smaller, slower ships than on larger, faster vessels. And let's not forget that there are other ways to save cost, like digitizing paperwork and moving administrative tasks to shore.

"Operators are having problems finding people to work on ships. A shore-based work environment is widely seen as more attractive, so highly automated and remotely operated ships could provide new and attractive shore-based jobs for highly qualified employees."

System engineering and software engineering also pose challenges to progress toward autonomy. "Capability among players is a major issue. The OEMs are better situated than most yards to take the lead here, because OEMs understand system integration, with capabilities in both systems and software engineering."

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Pierre Sames
Group Technology and Research Director
DNV GL

The road unfolds before you

So how does Sames believe the shipping industry will react to the changes that growing autonomy is bound to bring? “First the yards will be affected. Then the most traditional operators, those without the competence or the capacity to operate autonomously. New business models will also emerge, with power and potentially ships as a service, and many more ‘pay-for-play’ solutions.” Reiterating his long-term perspective, Sames concludes: “It will not impact all segments at once, and some perhaps not at all.”

He cites an example from the past: “When LNG as a fuel was being explored, in 2001 Norway started using LNG for ferries. No international regulations or class rules existed at the time, so they started working to develop early class guidelines. The IMO processes started in parallel to this. Six years later, the IMO had interim guidelines, and another 10 years later the IGF code entered into force, setting out internationally accepted requirements.”

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If we are going to find a way forward, we need to have pilot projects on the water.

Sames believe it is reasonable to expect a similar timeframe for autonomy. “Autonomy is more complicated, but more players stand to benefit.” These factors could balance each other out in determining the time required for industry uptake, he proposes. “But if we are going to find a way forward, we need to have pilot projects on the water. We need to keep taking small steps, each providing value in themselves, to find out where we want to go with this opportunity.”

02
Energy mix

Building better by building green

The key to establishing an economy based on renewable energy, according to sustainable development advocate Rachel Kyte, is a commitment to structural investments: “Unless a green infrastructure is put in place soon, we won’t make the transition in time.”

Dean of The Fletcher School at Tufts University, and the first woman to lead the USA’s oldest graduate-only school of international affairs, Kyte also serves as the Special Representative of the United Nations Secretary-General for Sustainable Energy for All, and co-chair of UN-Energy. Kyte attended the 2019 World Economic Forum as one of the conferences ‘energy stewards’, not in a formal role, she says, but still firmly in the middle of the discussion.

Now more than ever it is important to invest in green energy infrastructure.

“At Davos we could see that parts of the world are in fact coming together on green energy infrastructure,” she reports. “There is growing cohesion between ports, shipping, refineries, railway networks, and trucking, and we have producers and off-takers in places like Rotterdam, Australia, and Japan.”

But if progress is to be made toward decarbonization goals, she believes stakeholders will have to move forward quickly on the structural shift to renewables. “There is some resistance to infrastructure investment already, and there are growing signs of underinvestment. We have to move past the failure to deploy investments. Now more than ever it is important to invest in green energy infrastructure.”

Seeking maritime momentum

While the maritime industry has shown signs of movement, Kyte believes that shipping should be enacting even more aggressive measures than those prescribed by its governing body, the International Maritime Organization (IMO).

“If a percentage of the fleet committed to zero net emissions now, say 1-2 percent, that would create enough of a market signal for green hydrogen or ammonia producers to start ramping up. We could predict a certain demand, and owners could commit to the shift.”

But pivotal stakeholders are reluctant to make the first move, she says. “Fuel companies are willing to commit to making green fuel, but in the absence of government pressures or incentives, we need more pull from the shipowners to guarantee uptake.”

No nation left behind

The current green shift concept focuses on the developed world, Kyte notes. She questions whether there will there be sufficient industrial capacity in the developing world to achieve a global shift. “There is very little planning around that idea at the moment, but it will gain momentum as emissions grow in these places. The International

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Rachel Kyte
Dean
The Fletcher School
Tufts University

Monetary Fund should consider how it supports green infrastructure with its funding, as opposed using resources to support incumbent and outdated infrastructure frameworks."

While development in Europe could be part of a European Green New Deal with backing from the European Investment Bank, Kyte points out that this kind of cooperation is not as easy outside of an economic union.

"The transfer of energy is easier in a well-developed policy environment than in an emerging infrastructure. But how much discrepancy can we handle at once? Too much variation in the speed of adoption will make it difficult to exploit advances across national boundaries and jurisdictions," Kyte warns.

Productive policymaking

The good news story, she says, is that the debate on hydrogen is maturing. "Use of hydrogen is more about heavy vehicles now, trucks, busses, trains and ships, and this opens the doors for commercial development and innovation. Individual corporate buyers will need available hydrogen or ammonia, and the market assumes that carbon will be priced, which in turn will incentivize hydrogen development."

The question for Kyte is whether industry alone can ramp up infrastructure quickly enough to supply sufficient green hydrogen. "The industry needs to get busy doing what they can to support development of the infrastructure and the value chain. A proactive or aggressive policy would speed things up, but this has not happened yet."

Policy must also take a role in ensuring safety and establishing standards in order to boost confidence in new solutions, she says. Regulatory uncertainty or policy reversals could all slow down the process. "There are doubts about the greenness of technologies and the viability of infrastructure investment. Both public and private investors will need to see incentives, and this requires a clear policy element."

The UK, the Netherlands, Denmark, New Zealand and South Korea are all examples of countries that could move forward on green energy, she says. And while the federal government in the US is not driving development, Kyte points out that they still allow individual states to act. "Lack of national support and coordination will slow the process down, but the shift will still happen on the state level. There are plenty of potential investors out there."

The time has come

On the timeline for realizing the green shift, Kyte is a realistic optimist: "Listening to the big multinationals at Davos it was clear that they have ambitions, but also that achieving these will require the confidence to make major investments." The scenarios presented by Shell and other energy majors stipulate the need for hundreds of billions of dollars in investments over the next ten years, she says, not just in green fuels, but also in ports and efficient transportation.

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This is a moment of reconstruction, much like post World War II, or after the fall of the Berlin Wall, but it has to happen in the next 10-20 years.

"This is a moment of reconstruction, much like post World War II, or after the fall of the Berlin Wall, but it has to happen in the next 10-20 years." It can be done, Kyte claims, but will require a 'Marshall plan moment'. "That's what the G7 and the G20 should be talking about now," she emphasizes.

"It's not just about getting off coal, it's about what we need to build in its place. I worry that every day we don't invest, we just make it harder."

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Editor's note: The interview with Rachel Kyte was conducted before the Covid-19 pandemic began to impact global society. Kyte adds that green hydrogen, now more than ever, should be included as an element in stimulus packages, "to ensure that we build back better by building green."

Energy sources and carriers
Pathways to compliance

The fold-out infographic to the right presents an overview of the energy sources, carriers and converters that will help the maritime industry achieve emissions goals, both current and future.

"Hydrogen can be produced using renewable energy, or be made 'blue' through CO_2 capture," explains Jostein Bogen, Vice President, Global Product Manager Energy Storage & Fuel Cells at ABB Marine & Ports. "Hydrogen can be used in production of different types of synthetic fuels, or e-fuels, which can then be used in internal combustion engines or in fuel cells. We will need to use hydrogen as an energy carrier to reach emission reduction goals for shipping, and in line with the Paris Agreement," Bogen emphasizes.

He notes that biofuels are playing an increasingly important role, but still primarily as drop-in fuels to reduce carbon content. "Biofuels are generally not seen as a 100-percent solution, but more as additives or supplements," he says.

Bogen points out that the process of creating energy to drive fuel cells is fairly straightforward, adding that fuel cells and internal combustion engines can be used in combination to provide greener power solutions.

In addition, he believes that marine transport will likely figure centrally into solutions for carbon capture and storage, as pipelines are simply not feasible for all transport of CO_2 due to geographical and other restrictions. "This is a good example of what we mean when we say that shipping is part of the solution," Bogen concludes.

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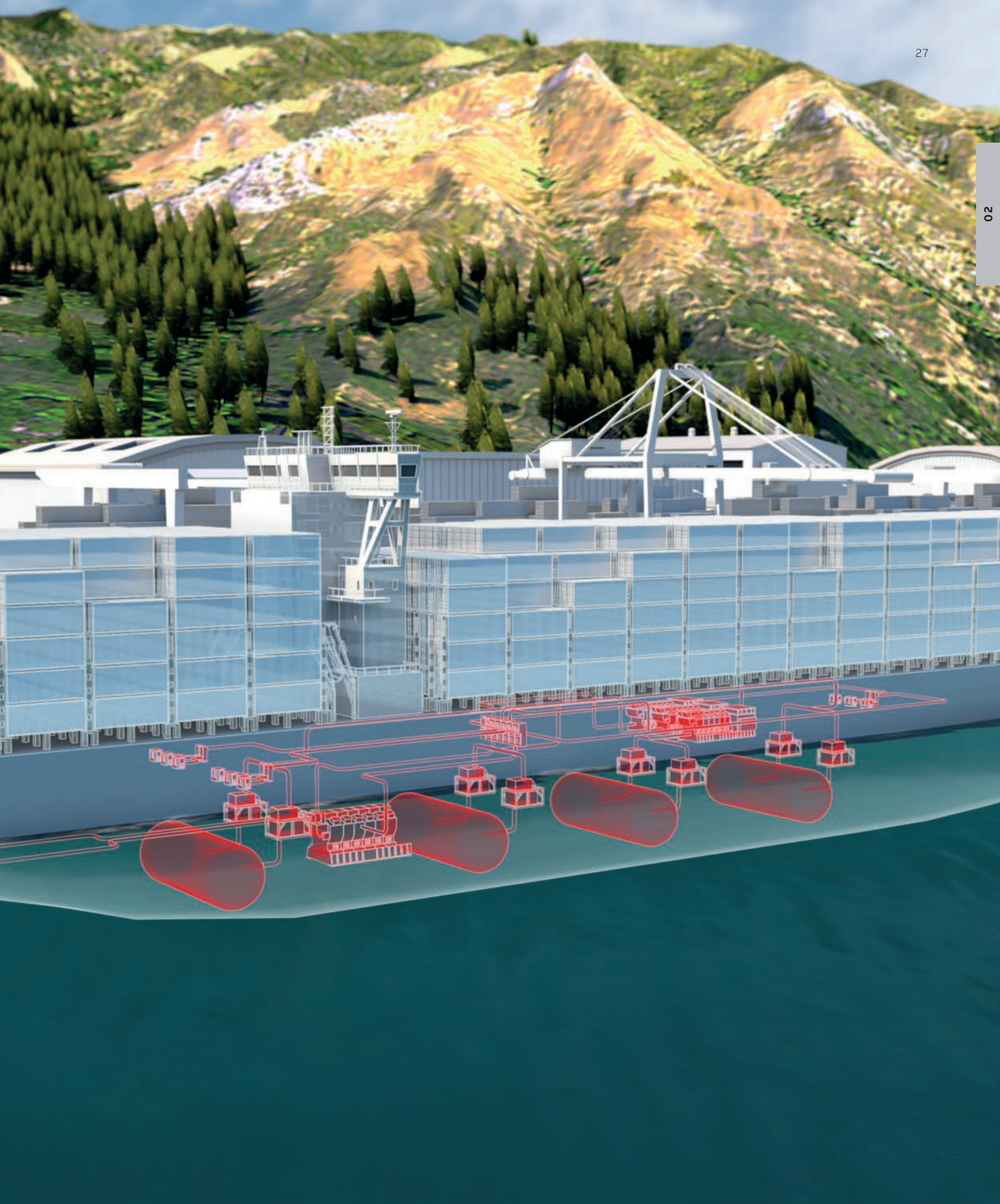
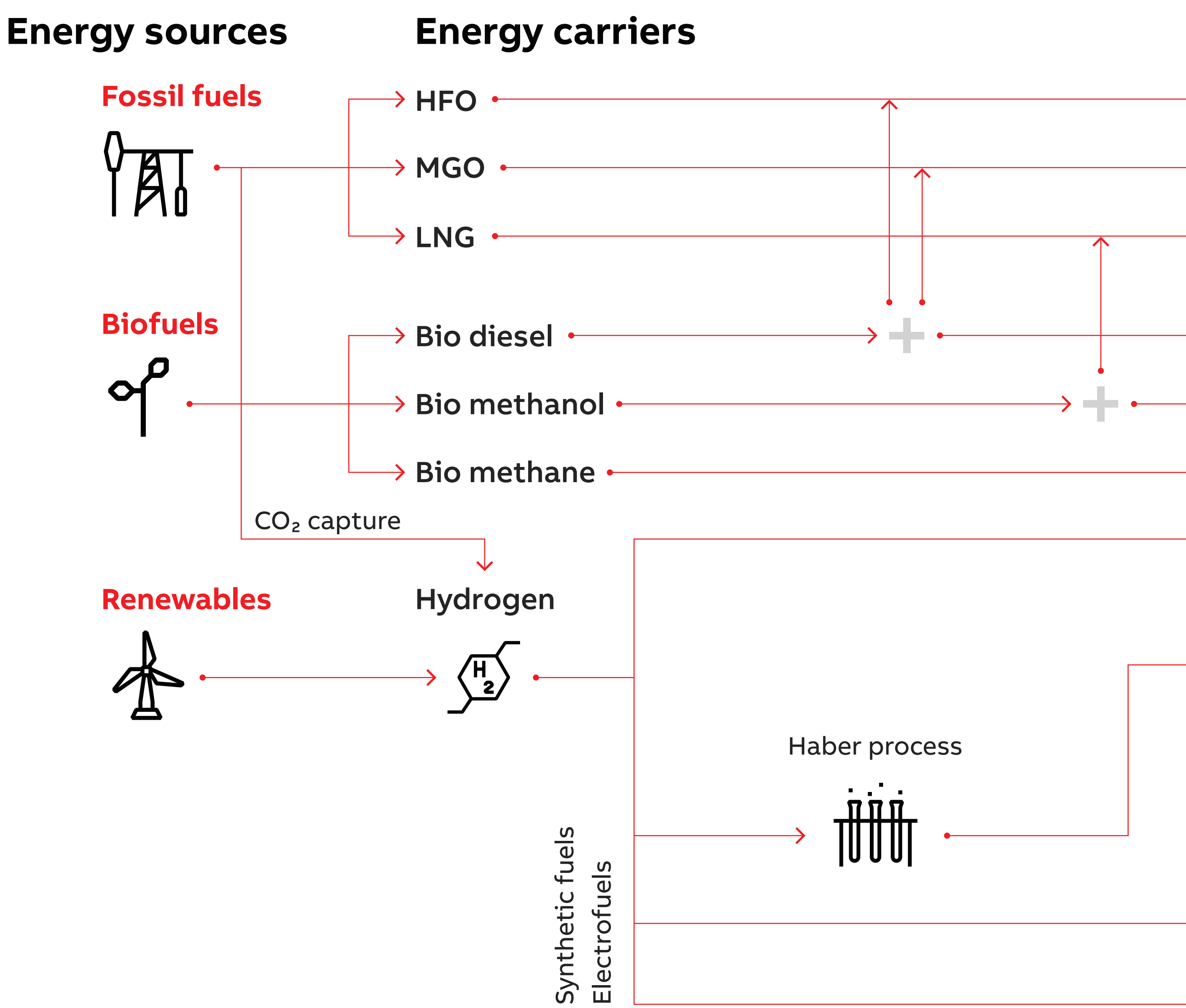
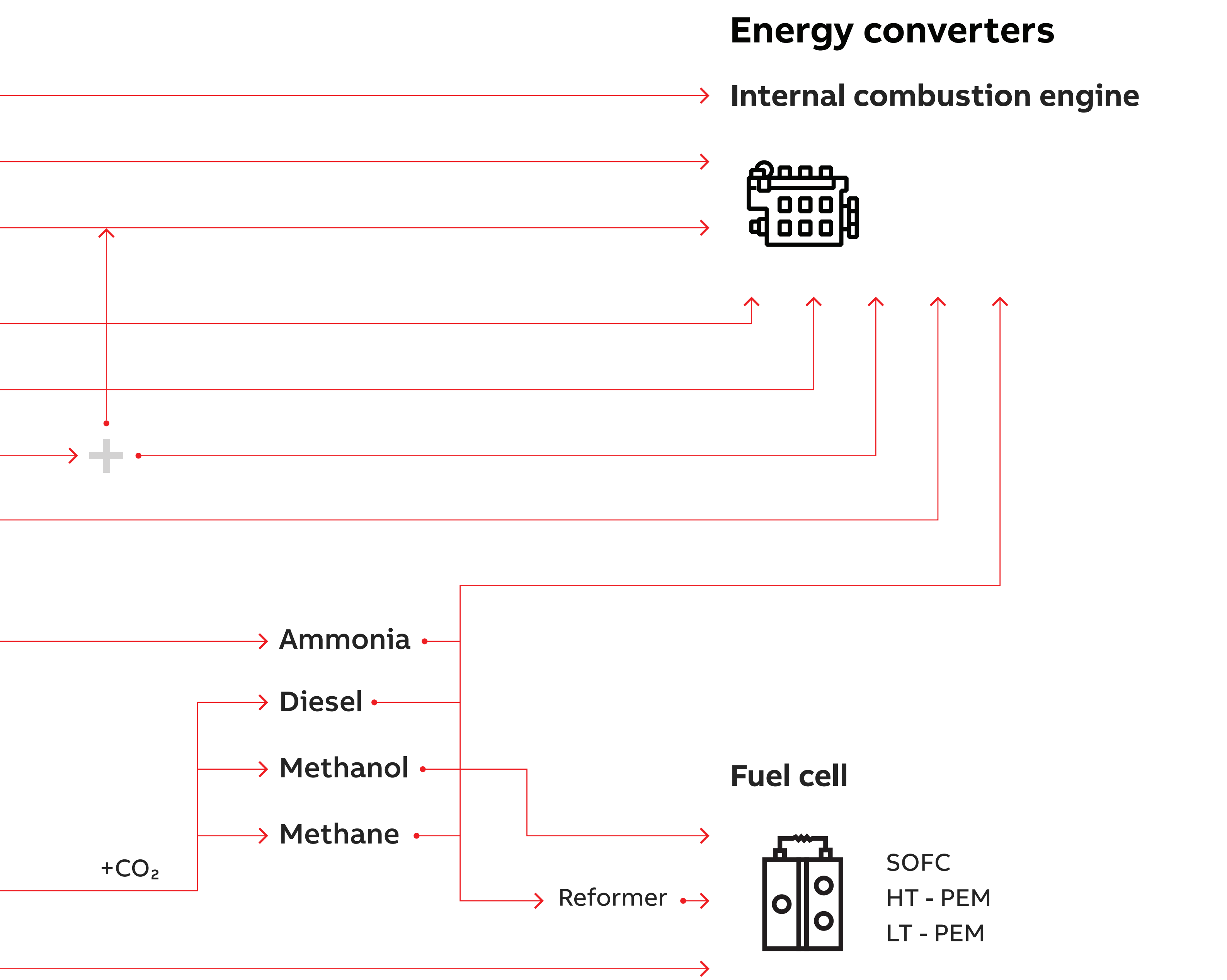
Jostein Bogen
Vice President
Global Product Manager
Energy Storage & Fuel Cells
ABB Marine & Ports



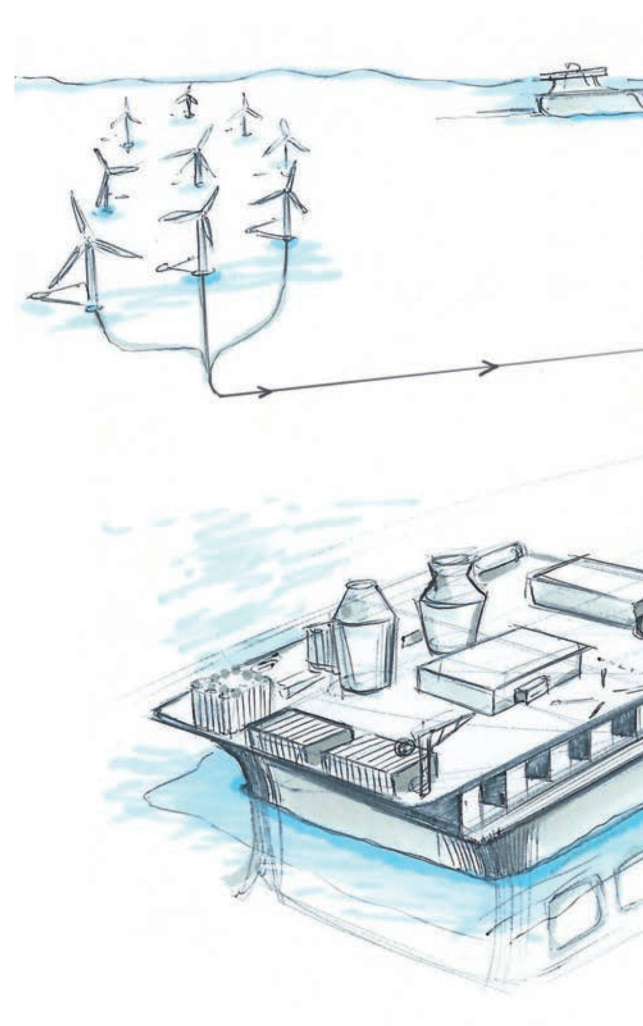
Fuels for current and future compliance




Energy converters
Internal combustion engine
Ammonia
Diesel
Methanol
Methane
+CO₂
Reformer
Fuel cell
SOFC
HT - PEM
LT - PEM

The floating filling station
Bunkering zero-emission fuel at sea

Much like a filling station by the roadside, a new concept may allow ships to bunker on the go, with clean, green fuel created using the power of nature.



ZEEDS, or Zero Emission Energy Distribution at Sea, is a novel concept using wind and solar power to produce hydrogen, ammonia or liquid biogas at sea, with production and bunkering initially located along The Northern European Shipping Highway. The partners are Equinor, Kværner, Aker Solutions, Grieg Star, DFDS and Wärtsilä.

Central to the concept is a system of offshore hubs that will produce, store and distribute clean fuel to vessels. The hubs are designed as gravity-based structures in shallow regions and potentially semi-submersible floaters in deeper water. Clean energy for topside fuel production will be supplied by around 75 large wind turbines per hub. One 12MW turbine can produce enough energy to fuel one ship, meaning that each hub could potentially produce enough fuel to supply 65 vessels per day.

“Our goal is a faster route to zero-emission shipping, but the goal has to be met with 100 percent renewable energy,” says ZEEDS project spokesperson Cato Esperø. The idea is to close the gap between the present situation and future needs, based on the 17 UN sustainable development goals.

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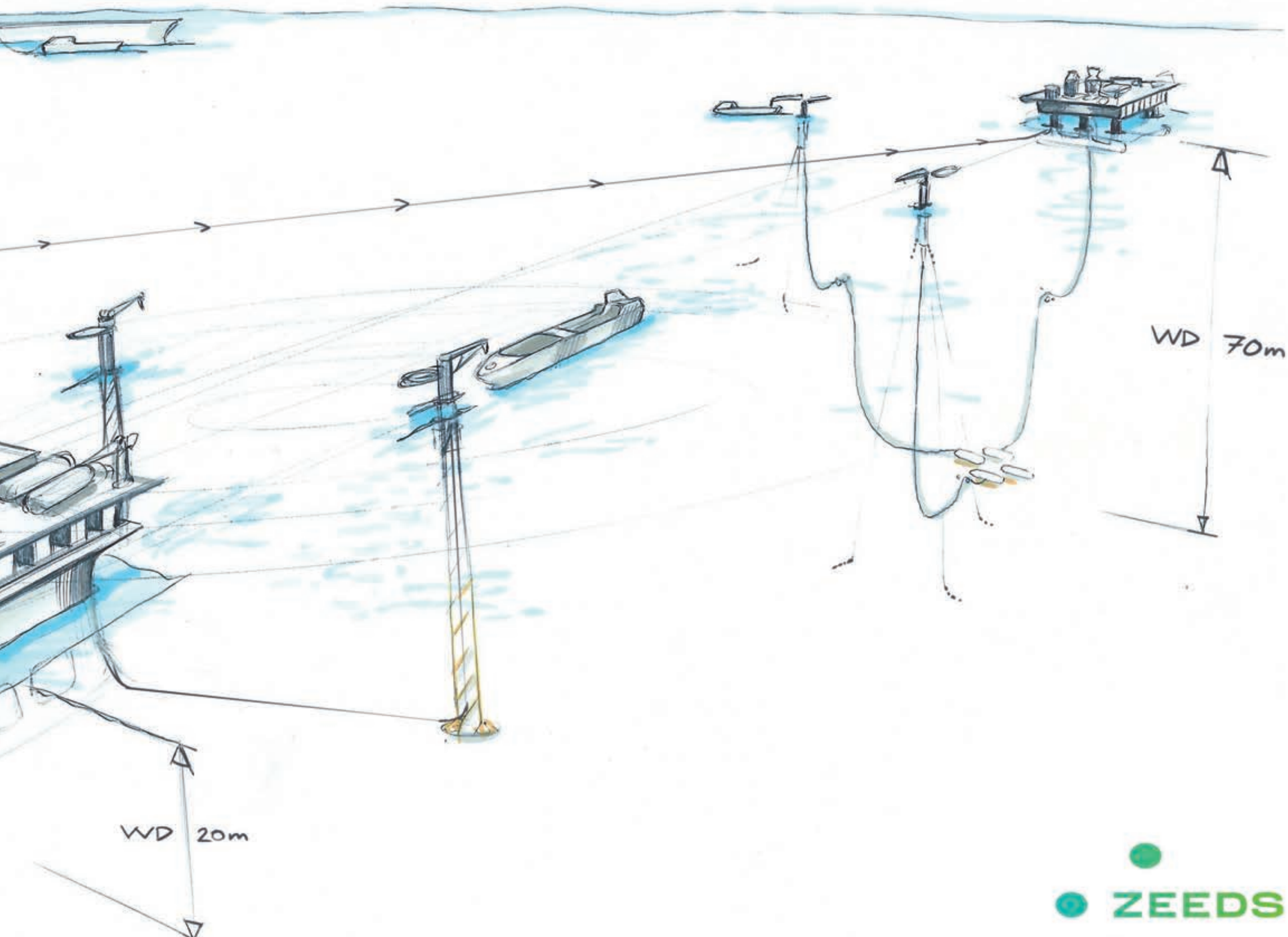
ZEEDS concept sketch



ZEEDS

"Imagine a network of clean energy hubs placed near the world's busiest shipping lanes, capable of supplying and distributing clean fuels to the global fleet," Esperø says. "It sounds ambitious, but if we are truly serious about managing climate change, we need big ideas and bold action."

Combining competence

Such a multi-faceted project requires what Esperø calls "composite competence". "We knew we needed energy, engineering and construction players, coupled with power suppliers, and global and Nordic shipping. What all the different project partners have in common is a sustainable perspective."

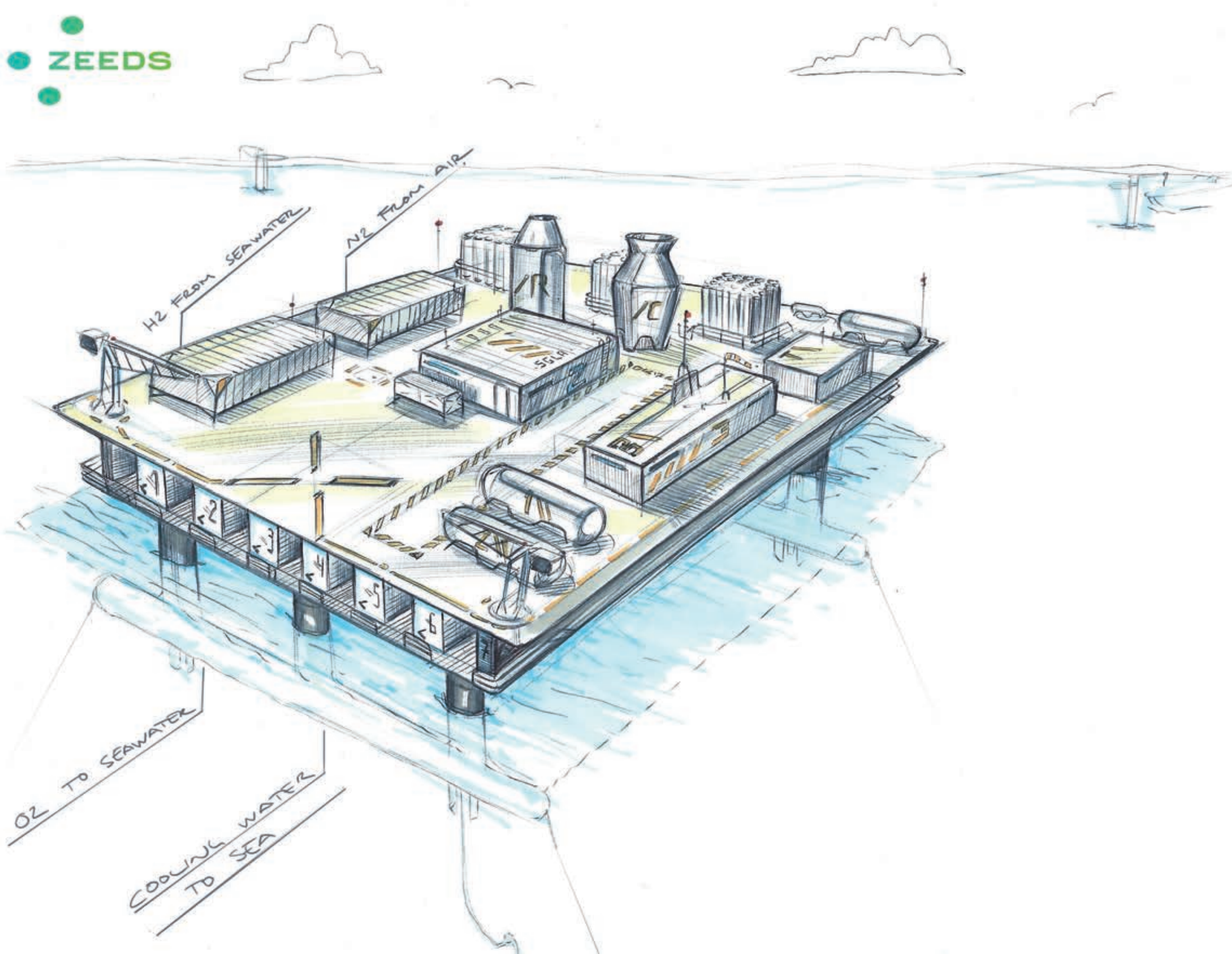
He points out that the partners are not necessarily competitors, but that they may be in certain contexts. "This is one of those situations where we can compete and cooperate as needed. We have a common challenge, and we need to agree on a common goal. Once that is done, all parties have to share what they can to achieve the goal."

The project defines most of the workflows, but partners will also work on their own initiatives. "And along the way we will of course redefine and recalibrate assignments," Esperø confirms.

ZEEDS: why and how?

"Public opinion and regulations have built up the argument for alternative solutions," Esperø says, but he believes that the current concept of clean shipping lacks a suitable fuel in order to be realized. "We believe that by addressing the supply, storage and distribution chain, we can accelerate the switch to cleaner shipping fuels."

— ZEEDS concept sketch



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Cato Esperø
Project Spokesperson
ZEEDS

The idea of placing hub installations adjacent to shipping lanes is not without its challenges, Esperø acknowledges. “We identified hubs in strategic locations, presented the concept, and asked the question: Is this feasible?” The result is a concept that should be scalable and flexible for global application, he says. The project is looking to utilize existing technology, but assembled in new ways, incorporating further development goals for selected technologies.

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Our goal is a faster route to zero-emission shipping, but the goal has to be met with 100 percent renewable energy.

The right fuel in the right place
“The industry has not yet decided which is the right fuel,” Esperø points out, “so we had to land on one. We started with hydrogen, but ammonia is a hydrogen product, and arguably easier to work with, with a higher energy density than hydrogen.”

Though ZEEDS’ current focus is on green ammonia as a feasible zero-emission fuel, given that it can be used on existing LNG-powered vessels without major modifications, the concept is classified as “fuel agnostic”, with the possibility of including fuels such as hydrogen or liquid biogas.

Ammonia would either be stored on the installations or in seabed tanks using water pressure to keep the fuel liquid. Distribution would use ship-to-ship (STS) bunkering at sea, minimizing operational downtime and avoiding port congestion. Bunkering would be performed by autonomous units dubbed Energy Providing Vessels (EPVs), fueled by their own cargo and with a range of 50 nautical miles around the mother hubs.

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Imagine a network of clean energy hubs placed near the world’s busiest shipping lanes, capable of supplying and distributing clean fuels to the global fleet.

Fueling a breakthrough
“The ZEEDS concept would require a new type of infrastructure and a new supply model, and this kind of renewal requires a realistic incentives program. Then the question becomes, should we use the carrot or the stick? Should society or business act as the driver? In any case, we need incentives to get started.”

He underscores that collaboration is the key. “Together, we can awaken the public to the new possibilities. The spirit of the project must be generous, open, and trusting, but we must also have sufficient drive and progress. We have to be both high-energy and high-level in order to make it work.”

A new energy model
Yours, mine and ours

Short-travel, sustainable products are gaining traction with consumers everywhere. Now the Dutch startup WeSpark is building up an ecosystem for locally produced and consumed electric power. The concept is catching on, with economic and ecological benefits for both customers and communities.

Jurrien Baretta is managing director of WeSpark, but she gives the impression that the role is more of a practical necessity. “WeSpark is a cooperative, so our customers are both members and owners. All the benefits we generate flow back to the members.” Located in the city of Zaandam in the Netherlands, WeSpark deals only in renewable energy. “Essentially we are sharing energy from the sun and the wind,” Baretta says.

Whether customers are pure consumers or generate their own energy, WeSpark can connect them to a green grid. They have teamed up with a small high-tech company to organize trading on the Amsterdam Power Exchange market (APX), where prices fluctuate every 15 minutes depending on supply and demand. “We forward these prices to our members,” Baretta relates. “For a small fee to cover our costs, they have continuous access to actual market prices.”

> This concept reduces the burden on distribution grids, but power loss in transportation is also reduced, so less energy goes to waste.

Transparent pricing allows WeSpark customers to hedge against future prices based on known consumption patterns. “Static pricing has to compensate for fluctuations, but we can use them to our customers’ advantage,” Baretta says. She adds that the model also encourages behavioral adjustments, as customers can plan to use more energy when prices are lower, and reduce consumption when demand is higher.

Taking less, giving back more

The money WeSpark makes is invested in new infrastructure that benefits members. “We are investing in smaller windmills, due to some resistance against the giant turbines. Efficiency is lower, but there is a higher degree of acceptance,” Baretta says. WeSpark also sells surplus energy from solar panels that continue to collect energy when their owners are away, and not able to use the energy they produce.

WeSpark plans to introduce energy storage, and they are looking into local green hydrogen production. “We hope to generate enough of a budget to expand into new technologies that will optimize the concept even further,” Baretta says.

The WeSpark marketing concept is as grass-roots as their business model, engaging local sports

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Jurrien Baretta
Managing Director
WeSpark

clubs to spread the word among their members. “Sports clubs are very popular in the Netherlands. Most people belong to one kind of club or another. We get clubs to do marketing by awarding them 10 euros for each new WeSpark membership. It’s basically word-of-mouth, and it benefits both the clubs and WeSpark,” Baretta says.

“We are only getting started,” she emphasizes. “We have some business customers, but no households yet. We expect official approval for supplying private homes soon, and our goal is 10,000 customers in the near future.”

Operations with a larger footprint are also potential customers: “For example, the Port of Amsterdam could use WeSpark to help supply shore power to ships, especially since there are already some windmills in that area that could be connected to our initiative. And when the port doesn’t need the produced power, it can be delivered back to the grid and serve the households in the vicinity.”

A model for the future
The practical premise of WeSpark is to keep energy as close as possible to where it is generated, or “use it where you produce it,” as Baretta puts it. “This concept reduces the burden on distribution grids, but power loss in transportation is also reduced, so less energy goes to waste.”

“Our ultimate goal is to combine commercial and environmental sustainability. Right now, we are just keeping our heads above water, but with our concept, profits that are now going to the big electric companies can be reinvested in sustainable power,” Baretta says.

Does Baretta see a broader market for the WeSpark model? “The model is mobile. All it takes is for people to join together as a community, and bring the benefits back to group,” she says. “But it still provides individual options. You can use the power you generate, or you can sell it. Either way it keeps cost down and makes power generation and consumption more affordable, and more sustainable.”

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The practical premise of WeSpark is to keep energy as close as possible to where it is generated.

03
Today's enablers

Azipod® propulsion enables key Arctic climate research expedition

Proving that a vessel of modest power and proportions could navigate the extremes of the Earth, the Norwegian Coast Guard's KV Svalbard carried an international team of climate researchers to the North Pole in August of 2019, aided by the operational capabilities of ABB Azipod® propulsion.

The research expedition was led by the Nansen Environmental and Remote Sensing Center (NERSC), with funding from the Research Council of Norway and the EU HORIZON 2020 program. The mission's main purpose was to improve collection of on-site observations in the central Arctic Ocean. "Satellites provide surface measurements that are excellent for monitoring the changes in the sea ice cover. But in order to understand the large changes taking place in the Arctic, we need better information on how warm and dynamic the ocean is under the ice," says Hanne Sagen, research leader at NERSC.

It is urgent to improve ocean observational capacity in Arctic.

"It is urgent to improve ocean observational capacity in Arctic," Sagen emphasizes. "The data collected will be used to check whether climate models are able to reproduce the observed changes, which will in turn be used to improve climate projections. Better climate projections will help us to plan and adapt to climate change, and that will impact millions of lives around the globe."

KV Svalbard's task was to help deploy a system of drifting ice buoys and seabed-anchored underwater moorings equipped with sound sources and receivers. "The Norwegian Coast Guard has historically partnered with the Coastal Administration on their ice-going projects," says senior engineer Andreas Kjøl of the Norwegian Coastal Administration. "Navigating in the central Arctic requires strategic route planning using sea ice information from a large number of satellites, and that is where our expertise in ice analysis becomes useful."

Mission accomplished

KV Svalbard is an icebreaking offshore patrol vessel designed for navigation in one meter of multi-year ice. The 104-meter vessel features two 5MW Azipod® propulsion units. The goal of the expedition, which required more than one year of detailed planning, was to reach as far north as possible. Kjøl notes that the team was particularly pleased to have made it the entire way to the North Pole.

"The combination of thorough preparation, vessel performance and crew experience was the key to success," he confirms. Ice status was monitored for six months prior to the expedition, and a route to the east of Svalbard was selected for lighter ice coverage, though still challenging for a vessel the size and power of KV Svalbard. "Keep in mind that this is the region with the most extreme ice conditions

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KV Svalbard at the North Pole

on the planet. The success of the mission was a major accomplishment given the physical and environmental parameters."

Though KV Svalbard has operated for years in the Arctic, the team expected to encounter challenges with thick multiyear ice in the higher latitudes. "We were even prepared to freeze in due to waiting, but this never happened," Kjøl says.

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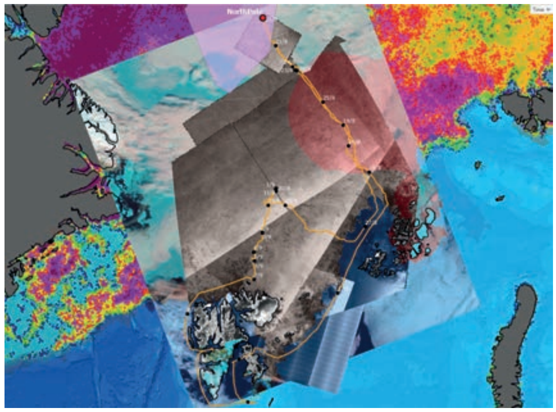
Better climate projections will help us to plan and adapt to climate change, and that will impact millions of lives around the globe.

Azipod® propulsion performed admirably
Deploying each of the moorings in the demanding Arctic environment required three days; one to locate the desired position for the mooring, one to deploy the mooring, and a third to deploy and position a network of transponders – communication devices that receive and send signals – around the mooring. The deployment operation demanded both skillful planning and execution, and a nimble ship. The maneuverability provided by Azipod® propulsion was a big advantage, Kjøl reports, not just for general navigation, but in situations requiring more finesse. "It gave us more options, like backing in to the ice to safely deploy equipment and make camp."

KV Svalbard employed several maneuvers to assist forward propulsion during the mission.



The navigation of the ship required extensive analysis of high resolution Earth Observation data from several providers and satellites e.g. Synthetic Aperture Radar data from Sentinel 1, Radarsat 2, and Cosmo Skymed. AMSR2 passive microwave data were used to observe the ice concentration (color coded). The optical images (e.g. Terra Modis) were, under cloud free conditions, used as support to detect open leads and ridges. Automatic Identification System (AIS) was used to observe the details of changes in ice drift, both via satellites and buoys deployed around the ship.

"We could induce heeling with pod propulsion, what we call the 'duck walk'. The rocking motion gives the ship more space in the ice. The helmsmen are very fond of the Azipod® units because of options like this that allow them to keep up momentum."

The voyage proved to be a newsmaker within the realm of ice navigation. "We were the first Norwegian vessel to reach the North Pole, and this sends a signal to the icebreaker community that independent polar navigation is possible," says Kjøl. "We also proved that Azipod® propulsion can enable smaller vessels to handle multiyear ice."

Keeping watch over the water

Moorings deployed during the KV Svalbard Arctic mission are part of a basin-wide acoustic system to measure mean ocean temperature – average temperature during a pre-defined time period. Each mooring carries acoustic and oceanographic instruments mounted on four kilometer-long cables kept vertical by floatation elements and tethered to the sea floor by anchors. The system has two low frequency sources, one positioned in the Nansen Basin and one in the Beaufort Sea, each emitting signals received by hydrophone arrays on moorings hundreds of kilometers away. "Sound waves travel faster in warmer water than cold," Sagen explains. "A temperature increase of one degree increases the speed of sound by four meters per second. Measuring the varying speed of sound waves allows us to obtain accurate mean ocean temperature data."

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The combination of thorough preparation, vessel performance and crew experience was the key to success.

Sagen tells that similar measurements were made in 1994 and 1999, with a 0.5 degree increase in temperature observed over those five years. "It has been 20 years since the last measurements, and this has been perhaps the period with the biggest environmental changes in modern history." The acoustic system allows ocean temperatures to be measured over a 2,500 km range in just about half an hour. "Using a research vessel to obtain traditional oceanographic profiles across the same section, it would take weeks to collect

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KV Svalbard with the deployment of ice tethered profiler (ITP) buoy at the North Pole in the foreground. The ITP autonomously measures oceanographic profiles while it drift with the ice. These data are sent back to scientists at Woods Hole Oceanographic Institution in near real time via IRIDIUM.

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Commanding officer Geir-Magne Leinebø and expedition leader CAATEX Dr. Hanne Sagen at the North Pole

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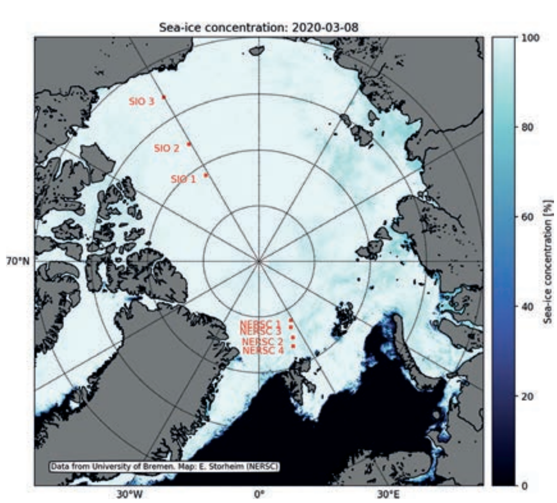
Figure 2: The geometry of the 2019–2020 Coordinated Arctic Acoustic Thermometry Experiment (CAATEX) and the Integrated Arctic Observation System (INTAROS) experiments. The acoustic moorings at SIO1 and NERSC1 carry both source and receivers. There are four vertical receiving arrays: SIO2, SIO3, NERSC2, and NERSC3. The mooring at NERSC4 (green) has conventional oceano-graphic instrumentation to measure temperature, salinity, and currents. The SIO moorings were deployed by Scripps Institution of Oceanography using the US Coast Guard ice breaker Healy. The sea-ice concentration on 31 October 2019 is from the Advanced Microwave Scanning Radiometer 2 (AMSR2) dataset provided by the University of Bremen (Spreen et al., 2008). (Source: seaice.uni-bremen.de/sea-ice-concentration)

the same data. The acoustic system is designed to give instantaneous and reliable measurements of the mean ocean temperature with an accuracy of 10-50 millidegrees for the entire Arctic Basin every 36 hours for a full year."

Once deployed, the moorings are covered by sea ice, making it impossible for them to transfer information to satellites. The solution is to store data in each unit until recovery, scheduled for autumn 2020.



Right to be there

Kjøl acknowledges concerns over more vessels sailing further north, and more often. "This is a relatively new phenomenon in the High North, and there are fears that more frequent passages may have a permanent impact on the ice structure," he says. Nonetheless, he believes the benefits of research expeditions far outweigh negative consequences. "On this mission we acquired knowledge that is vital for the informed management of the polar regions. This helps us not only to understand climate change, but informs decisions on how to manage polar environments responsibly."

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We proved that Azipod® propulsion can enable smaller vessels to handle multiyear ice.

All experience gained during planning and execution of the mission is contributed to the international search and rescue exercise project SARex Svalbard, he tells. "The stakeholders are dedicated to sharing results to strengthen our common knowledge base, and to help ship operators be better prepared to ensure improved safety for Arctic shipping."

ABB Marine Academy rises to meet shipping's new needs in the north

Assigned with shipping gas from the Arctic port of Sabetta to the Far East and Europe, energy transport major Teekay was faced with new challenges in the Yamal LNG project. Through an innovative training program, ABB is helping them to safely tackle the demanding task.

Teekay's newest gas tankers are equipped with Azipod® propulsion systems and classed to Arc7, the highest ice class rating for merchant vessels. "At the start of the project, ABB Marine & Ports' senior management team spoke with the Yamal LNG joint venture about our training needs with these new vessels," says Arron Grant, Training and Recruitment Manager, Teekay Gas.

Based on this dialog, ABB compiled a package related to all onboard equipment, not just the Azipod® propulsion. The response has been unconditionally positive.

"Seafarers are very honest people. They tend to say what they think, and we have yet to hear anything negative about ABB training," Grant observes, referring to both informal feedback from the crew and reviews in the ABB system. "Every single response from our officers on the ABB courses has been at the level of 'excellent' and 'highly recommended'."

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We need to provide the highest level of training, equipment, and support.

ABB has training centers in seven countries on three continents, all staffed with knowledgeable, highly professional instructors, according to Grant. "Crew members typically attend training courses during their shore leave. They wouldn't spend two weeks away from their families if they didn't feel that the training was beneficial, and that is an extremely high standard to meet."

Ship as a unit

The expanded training package was built on ABB's dedicated training for their own equipment. Courses for Teekay now address the various aspects of the machinery space, including propulsion, marine drives, generators and high voltage. "They bring it all together, addressing the ship as a unit," says Grant. "One day we might focus on a certain element, then look at how it links into related equipment. This gives the crew perspective on how the whole vessel can be affected by a single fault."

"We are always looking for gaps in officer training and developing new measures to cover these gaps when we find them," Grant says. "This means going beyond the standard requirements. ABB training places the crew in challenging situations in order to be sure that they are capable of handling any emergency that may arise on board."

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ABB Marine Academy

Many tasks – one team
On board a ship, deck and engineering officers have responsibility for different tasks, but ABB training emphasizes commonality among all crew. "The bridge is focused on operations and management, and the machine room handles the equipment. The holistic approach encourages collaboration between the different groups on diagnosing and fixing problems," Grant explains. "This is a very insightful approach to training. Some programs separate the bridge from the engineers, but you can't run a modern ship based on this type of dichotomy."

He also notes the importance of acknowledging the cultural differences between groups in the team. "This comes down understanding the day-to-day workings on board a ship. There are many subcultures on board, but the crew has to come together to create a common culture of safety."

Based on this insight, Teekay is increasingly promoting the concept of Operational Leadership. "In this model, all crew members are accountable to each other. There are no restrictions on input. Anyone can suggest improvements or report an unsafe act, or simply ask questions," says Grant.

The training is not exclusive to new hires – veteran officers are also invited to participate. "This applies mostly to those sailing on Yamal ships, but training in Singapore applies to other ships as well. Everyone can benefit from the training package," says Grant.

With reliance on technology growing, companies risk losing sight of the importance of the human factor, Grant reflects. "Every aspect of operations has a human element, and human error is behind 9 of 10 faults. We are working continuously with ABB to address this issue." More than just dealing with emergencies like firefighting or abandoning ship, he maintains that soft skills must be applied to everyday life on board: "It's about keeping the human element front of mind in everything we do."

Managing the extremes
While sailing the Northern Sea Route is not a completely new concept, liquified natural gas (LNG) transport is new to the Arctic, Grant points out. “These are fast vessels, and even with the highest ice class, the risks are not lost on us. We need to provide the highest level of training, equipment, and support in order to give the crew the best chance to operate successfully in these extreme conditions.”

Knowledge of sophisticated equipment is essential, but preparing for the extreme climate is an equally important part of polar survival training, he adds. “Even the tour lengths have been adjusted to adapt to the northern environment, taking into account the effect of extreme light and cold on the crew.”

ABB also offers Azipod® space safety training. “Inside the pod is a very demanding machinery space requiring specialized skills and knowledge,” says Grant. “Some of our officers were unsure whether ABB’s training was relevant, or whether it would just be a repeat of Teekay’s own enclosed space training. After having completed the ABB program, all of the participants felt that ABB had added something new.”

Building on trust
“Trust is a factor from day one, in all our communications with OEMs. We get an impression of how they operate, and what their standards are,” Grant relates. “Our level of confidence in ABB is based on their response to our needs. They are consistently prompt, proactive, and professional.”

Teekay regularly presents ABB with changing requirements. “It has never been a problem to implement changes underway, and 99 percent of our change requests have been met. All this helps to build trust in the relationship.”

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ABB Marine Academy

Building the case for additive manufacturing

RAMLAB at the Port of Rotterdam wowed the world when they presented the very first metal printed certified propeller. That milestone silenced doubters and signaled the arrival of 3D printing as a viable challenger to traditional marine parts manufacturing.

3D printing applies to both subtractive and additive manufacturing, either removing or depositing material to form objects. RAMLAB was established in 2016 to pursue a vision of printing metal parts on demand using wire arc additive manufacturing, or WAAM. In 2017, after only one year of operation, they produced the world's first 3D printed propeller, made up of 298 layers of nickel-aluminum-bronze alloy.

"That got a lot of attention," says Vincent Wegener, managing director at RAMLAB. "At the very least it was a myth-buster. Some claimed that we would never manage to produce a certified propeller at all, and then we did it in our second year. That opened a lot of eyes, and a lot of minds."

Conceived chiefly as an R&D initiative, RAMLAB's aim is to move additive manufacturing from R&D into commercial production. "The ultimate goal is to achieve full profitability. We have been investing in getting things working. Now we need to identify the parts that are relevant to print," says Wegener.

RAMLAB's main investor is the Port of Rotterdam, in partnership with InnovationQuarter and RDM Makerspace. "Submarines for the Royal

—
Vincent Wegener
Managing director
RAMLAB

3D printed propeller, named WAAMpeller

Netherlands Navy used to be built on this site. Now we are back to serving military customers, as well as billion-dollar companies." While the client list remains largely confidential, industries include oil and gas, energy, equipment suppliers, defense, and aerospace.

"Importantly, we also have a good relationship to Delft University of Technology," Wegener tells. "We offer internships, working closely with the professors. That means we have students, PhDs, and post-doctoral researchers working in the lab, coming from China, Italy, and Greece, in addition to Northern Europe."

He acknowledges that 3D printing could either be a threat or an opportunity for shipping, disrupting established supply chains, but also giving owners, operators and suppliers the chance to reduce inventory and transport costs. "Will it hurt or help the shipping industry? We don't know, but our philosophy is to embrace new technologies rather than fear them."

RAMLAB's current drive is toward automation and serial production, a key step toward commercial viability. "Technology is digitizing everything, including manufacturing. The parts manufacturing and supply industry has not been disrupted yet, but if we can be quicker, better, faster, and closer, they will have to respond."

Technology is digitizing everything, including manufacturing.

AI and machine learning will only speed up the additive manufacturing process and improve quality, Wegener believes. "This is the time when everything is happening, and we are in the middle of it all, just trying to ride the wave."

3D printing
Parts of a bigger picture

Speculation on the impact of 3D printing on the maritime industry has been running for nearly two decades. Now the first contours of a commercial 3D printing venture are emerging, with Wilhelmsen and six of its customers teaming up to shape a more sustainable future.

"Decarbonization is one of shipping's greatest challenges, but it also offers opportunities, and all stakeholders will be affected," says Nakul Malhotra, Vice President Open Innovation, Marine Products, Wilhelmsen Ships Service. "The expectations generated by current regulations are only the starting point. With an ever-increasing focus on the environmental footprint, we must challenge ourselves to constantly do better."

In their pursuit of low-carbon solutions, Wilhelmsen has chosen not only to look at reshaping the larger assets of ships and energy, but also to examine the opportunities available throughout their supply chain and product portfolio, including digital solutions for replacement parts.

> Decarbonization is one of shipping's greatest challenges.

Fitting the pieces together
Malhotra explains that the cost of replacement parts is largely tied up in inventory, freight and logistics. Part of the solution is printing parts at strategic hubs around the world, for pick-up by ships in transit. Connecting smart parts to the Internet of Things can also reduce their carbon footprint and cut costs along the value chain. "Basically, getting parts to talk to each other, or even to other parts of the ecosystem, in order to know in advance what part is needed where, and when," Malhotra says. "This is becoming possible because communication technologies are progressing to the point that vessels can communicate at scale, not least with each other."

Improved quality is another argument. 3D printing is the generic term for using machines to create physical objects from digital models, either by means of subtractive (removing material by grinding or milling) or additive manufacturing (constructing by layering or depositing material). "We can analyze why parts are breaking or wearing too quickly, and that allows us to print a better version of the part. Additive manufacturing also enables us to implement complex structures in parts, including incorporating different physical characteristics in the same item," Malhotra says.

But he is adamant that Wilhelmsen's 3DP initiative, through the early adopter program, is not competing with original equipment manufacturers (OEM) on parts. "We are very aware of intellectual property rights," he assures. "This is not a back door to get around manufacturers' rights.

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3D-printed scupper plugs, the first delivery from the Early Adopter program, made for Berge Bulk

We are working with the OEMs as an important part of this initiative." In addition, he points out that on-demand manufacturing can fill a need at the lower end of the market: "Most parts are generic, and many machines are outdated, with no replacement parts available on the traditional market."

Hitting the sweet spot

Proof of concept for has been established by printing the most complex parts, like propellers, but that alone will not lead to the broader adoption of the technology, Malhotra claims. "The crew or the managers don't care how a part was made, as long as it is fit for purpose. We call the current level we are aiming for 'comfort-critical', meaning that we can guarantee the necessary degree of security to customers wanting to use printed parts. Broader adoption of printed parts will be achieved first on a lower threshold."

When 3D printing technology began to emerge as viable, the talk was of installing printers on ships so they could generate their own parts. Malhotra offers his take on why this idea has not taken off: "Number one because additive manufacturing requires access to a broad range of materials. We have a library of over 80 materials in our print shops around the world, and this is simply not feasible to duplicate on individual ships. In addition, we need skilled and stable crew to run the machines. The solution is to hit the sweet spot with strategic placement of printing stations that are easily accessible to the global fleet."

Malhotra acknowledges that 3D printing presents a challenge to the traditional centralized manufacturing setup. “Some potential customers will try and deny the value of the concept, others will embrace it. OEMs are the same way. Some will be closed to change, and some open.” Shipping and freight companies are understandably concerned, he notes, but believes that 3D printing will probably not impact shipping volumes significantly. “In any case it is going to happen, and we believe it must be better to take the lead, rather than be playing catch-up.”

Beyond the hype

“3D printing is the current focus, but this is not a one-off initiative,” Malhotra emphasizes. “The story is bigger than that, and it started with recognizing the digital revolution as a mega trend in 2015.” He recalls that when the digital wave broke, many in the shipping industry began to make claims of being data-centric: “All of a sudden everybody wanted to believe they were Google.”

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Nakul Malhotra
Vice President
Open Innovation
Marine Products
Wilhelmsen Ships Service

As the hype of digitalization dies down, Malhotra believes that industry players will need to find their own areas of competence and bridge them with new age technology capabilities to create added value in shipping. “We are a 160 year-old company in the age of digitalization. As such, we need to create space between those responsible for running the core products portfolio of the company and the team focusing on innovation, but without separating the two,” he relates. “Why establish a totally disconnected start-up when we have all that knowledge to feed on? The bridge between ideas and experience is where the magic is made.”

The initial steps were taken in 2018 with the establishment of a venture team in the core product management group. The next phase in the evolution was to set up the Open Innovation team, launched in November of 2019. Following several months of early concept testing, one of the team’s first tasks was to forge a commercially viable way forward on 3D printing and additive manufacturing.

A new ecosystem emerges

The Wilhelmsen-led initiative is currently backed by Carnival Maritime, Thome Ship Management, OSM Maritime Group, Berge Bulk, Executive Ship Management and Wilhelmsen Ship Management, all of whom have signed up with Wilhelmsen’s Marine Products division as early adopters of on-demand additive manufacturing. Ivaldi, a digital manufacturing start-up out of Silicon Valley, has been engaged as technology partner, joining the expanding ecosystem together with DNV GL and Thyssenkrup.

“We do not have all the answers or the necessary resources ourselves, so we are looking to stimulate a wider co-creation environment,” Malhotra explains. “We need to partner with customers, suppliers, regulators and innovators in order to realize this amazing technology’s true potential. 3D printing requires a different ecosystem than traditional centralized manufacturing.”

There is a standing invitation for all interested parties to join the ecosystem, he assures. "As long as they are open to understanding the value propositions, now and in the future. We are looking forward to expanding the ecosystem. The only way to ensure success is to collaborate."

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The solution is to hit the sweet spot with strategic placement of printing stations that are easily accessible to the global fleet.

Time to eat the pudding
"It has been a long wait. Now people need to see if this is real," Malhotra maintains. "We have six early adopters with 10 ships each. That means 60 ships testing the concept and vetting solutions, starting with the most accessible products." Their aim is to build trust and confidence among the public and end users using a stepwise approach: "We have to test this out in real life. Success will be defined by moving from a group of early adopters to a larger number of fast movers. We have all the components in place to deliver this solution. Now we see if it works, and if people want to use it."

He emphasizes that the shift will not happen overnight. "This is a major development and it will require orchestrated and planned implementation. Ultimately consumers are going to drive progress in this field, all along the value chain from manufacturers, retailers and service suppliers to buyers. The benefits for customers must be clear if all players are to subscribe to the model."

User-centric bridge design
Enough is enough

It’s possible to have too much of a good thing. While advances in engineering and technology have made piloting a modern ship safer and more efficient, information overload and an excess of options can hinder as much as help bridge officers in doing their job.

Antti Matilainen is automation engineer who has been with ABB Marine & Ports since 2000. “Back then I was doing a lot of commissioning work, and after a while I began to question the usability of some of the designs being produced for operator environments,” he recalls. As solutions became steadily more sophisticated, Matilainen observed an increasing lack of connection between bridge equipment and the machinery it was designed to control. “That’s when I realized we needed to start putting usability first.”

To get things moving in a new direction, in 2015 ABB Marine & Ports revamped their bridge and automation research and development organization, strengthening the team with industrial designers. The focus shifted to user-centric design, striving to refine the logic that links the bridge with the machine room. “Our goal was to emphasize simplicity. We wanted to provide only the essentials needed to pilot the vessel,” Matilainen says.

Essential connection with customers

“We gather concepts where research and testing leave off and enrich them up to the product development stage. But we cannot do this by ourselves.” The key to enriching ideas, he says, is dialog with customers.

“We have co-creation agreements with our largest customers.” These are primarily the yards, but also captains, machine engineers, and operative crew are invited to participate in product development laboratory sessions. At this stage, Matilainen says, they are not focused on profit. “We are out to collect the raw material that will form the basis of future products. Collaboration and discussion are the main goals.”

Enablers of this creative exercise might be a simple table, paper cutouts, inexpensive screen mock-ups, even coffee cup holders. The low threshold allows participants to relax and be inspired, Matilainen relates. “In this kind of a setting, everyone feels comfortable. It gives us an opportunity to play around with design.”

He notes that end users are often the most motivated to seek out simplified solutions. “The process gives our customers the chance to see options they might not have realized were available.”

Holding up the business end

The collaborative effort also serves to cement mutual commitment to solutions, he says. “That is important for all parties. Usability has to be prioritized early in the design process. Once a design has been committed, it’s too late. We need to engage the team before building is initiated. The idea is to not interfere with shipyard contracts, but rather to give them the right input before they start building,” Matilainen says.

The team also needs to make business decisions along the way in order to be able to roll out a new design. "We have to calculate the added value for all stakeholders, so product managers and sales staff are involved throughout the design process." He reports that the team is constantly scouting for innovative technical and design solutions across all industries, not just transportation, all the while mindful of ABB design guidelines.

Matilainen emphasizes that prioritizing the end user does not stop with the initial design process. "We also use research to refine ideas. User studies are critical in this process," he says. "Evidence-based design is another way to ensure that the focus stays on functionality."

Circular collaboration

Matilainen and his team also have extensive collaboration with academia. Students are encouraged to do their thesis work across disciplines, in order to bring a wider range of perspectives to the design process.

Typically there are strong personalities dictating the direction of design, he tells. "Our idea is to concentrate on whether a design works or not." Engaging automation specialists, sea captains and industrial designers to assist the students enables the team to verify results on a broader scale.

"Using these resources, we have discovered new ways of operating vessels with multi-use levers that control the vessel, thrusters, and more." He is also aware that not all ideas are ready to be pushed out of the nest as soon as they are hatched. "We have come back to ideas after several years and used them in new solutions."

Seeking simplicity

Matilainen acknowledges that while offering welcome improvements, modern bridge solutions can easily generate technical details that users do not always understand. "This does not serve any purpose, so we need to challenge the rules, and sometimes that means leaving out unproductive information."

Avoiding operator overload is a key reason to strive for simplicity, he says. "We need to keep interferences to a minimum." One well-known issue involves widely disparate situations with the same alarm indicator. "It makes no sense to get the same alarm whether the coffee machine needs cleaning or the ship is sinking. Too much noise makes it hard to understand what is really happening."

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We needed to start putting usability first.

The ultimate goal is to integrate a holistic view of the entire vessel into designs for operator environments, Matilainen maintains. "We are striving to see not just the bridge, but all the elements of a ship, including propulsion, power, and control, and still keep it simple."

Trained as an engineer, Matilainen himself admits to believing that empty space was wasted space, until industrial designers advised him otherwise. "I thought a display was finished when nothing more could be added. In fact, it is finished when there is nothing left to take away." The challenge, he says, lies in learning what can be removed. "There is a still a long way to go to the ultimate simplicity, but we are getting there."

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04
Toward a sustainable future

Sustainable by design
Building a green future

Vestre outdoor furniture brightens urban spaces around the world, from Oslo's Aker Brygge to New York's Times Square. CEO Jan Christian Vestre wants to turn the Nordic company into the most sustainable furniture brand in the world – and he is right on track.

Vestre was making furniture that lasts long before sustainability became a universal concern, with park benches built in 1950s still standing strong against the harsh weather of Haugesund, a coastal town in southwest Norway. Today, the company is planning to open the world's most environmentally friendly furniture factory – the largest single investment in the Norwegian furniture industry for decades.

When it comes to the 'green shift', the manufacturing industry is not part of the problem, we are actually part of the solution.

Changing the world, one bench at a time
What started as a family business over 70 years ago has turned into what Jan Christian Vestre, grandson of the company founder, calls a 'democratic project'. When he took over as the CEO at age 25, he laid out a forward-looking vision for the company, not only as an endeavor to safeguard the environment, but as a commitment to make the world a better place.

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Vestre benches in Strynefjellet, Norway

"Some people find that naïve, but I don't care because naïve people change the world," says Vestre. "It will take trillions of dollars to eradicate poverty, to stop climate change and to reduce inequality between people in the world. We are part of all that." Vestre sees the company as a tool to change the world – by creating caring meeting spaces, proving that manufacturing industry is part of the 'green shift', and taking part in financing social sustainability.

When we choose materials, we achieve emission reduction in our own products, but we also challenge the steel and aluminum industries in the right way.

Sustainability is not only ingrained into Vestre's ethos – it is the driving force behind the company's business and operating models. Vestre continuously challenges the manufacturing process, with factories in Norway and Sweden running on renewable energy harnessed from solar panels. By 2025, the company aims to feed at least 20 percent of their surplus energy back to the grid, and in ten years' time, plans to operate with zero emissions altogether. Vestre's latest project, The Plus factory to be built in Norway, will generate 250,000 kWh of renewable energy and have at least 50 percent lower greenhouse gas emissions than comparable factories.

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Jan Christian Vestre
CEO
Vestre

"When it comes to the 'green shift', the manufacturing industry is not part of the problem, we are actually part of the solution," says Vestre, adding that the company – without exception – sources the most sustainable materials available, putting quality and environment above price. The Swedish steel used in Vestre furniture is produced with 30 percent less CO_2 emissions compared to cheaper alternatives from other parts of the world, and recycled aluminum from Norsk Hydro is considered to be the 'greenest' in the world.

"When we choose materials, we achieve emission reduction in our own products, but we also challenge the steel and aluminum industries in the right way," Vestre says.

Sustaining the business

Even though Jan Christian Vestre has more than tripled the company's turnover since taking the helm in 2012, proving that a business can be both profitable and sustainable, he says that profitability is not the key priority. "It's much more important to do things right, and with a long-term approach."

Thinking long-term is one of the reasons why Vestre donate 10 percent of their yearly profits to finance sustainable projects around the world. "If all Norwegian companies acted like Vestre and donated 10 percent of their profits, the Norwegian business sector would have matched the country's entire foreign aid budget twice over," Vestre says.

But how to strike the balance between sustaining the business and safeguarding the environment?

"We need to challenge some of our economic models," says Vestre. Companies that are not willing to rethink their approach may not survive in the long term, he adds, pushed by younger generations that have higher expectations and bigger demands when it comes to the environment.

Vestre products are manufactured in high-cost Scandinavian countries and come with a lifetime warrantee. "Our advisors tell us it's crazy, but I am certain about the quality and I know we are doing the right thing," says Vestre. "We do all these things and still we are profitable. Maybe some

Vestre outdoor furniture in Aker Brygge, Oslo, Norway

companies think too much about profits, maybe they should think more about their impact and how they can contribute to the greater good. I think they would be profitable then."

Pushing the limits, closing the loop
Climate crisis, Vestre believes, is tightly linked to what he calls a resource crisis – producing poor quality products and throwing them away, creating waste. "We cannot continue in this way," he states.

The design industry is driven by trends, and there is a push to have new products released every year – not a sustainable approach when fully functional furniture needs to be replaced because it's 'out of style'. Vestre operates with what the company calls 'Vision Zero' – making zero products that don't 'last forever'.

It isn't enough that Vestre push the limits its own environmental performance. With 150 of the company's products carrying the Nordic Swan Ecolabel – the official recognition for products produced sustainably in Nordic countries – Vestre challenges the organization to make their criteria even stricter.

Maybe some companies think too much about profits, maybe they should think more about their impact and how they can contribute to the greater good.

The company takes it even further, asking their customers to increase their requirements towards Vestres's sustainable practices, as well as the lifecycle costs of products: "Not only should we provide our customers with information about the costs of products after, say, ten years, but we should also have the legal responsibility to live

Vestre bench outside the King's Cross St Pancras tube station in London

up to our promise to deliver products that last forever. Imagine what a revolution there would be if companies made sure they made products with a long lifespan."

"We are testing out a new business model where we can return old and worn furniture to our factory, paint it, replace spare parts, make it look like new – and then sell, rent or lease it to a new project. This way, what feels old-fashioned for one, could be new and relevant to another."

Imagine what a revolution there would be if companies made sure they made products with a long lifespan.

This circular approach, Vestre says, can help the company reduce their own energy consumption by up to 80 percent. Another measure helping Vestre to optimize operations – and cut emissions as a result – is investing in new technology.

The company's factory in Torsby, Sweden, uses ABB's welding robots, which, Vestre acknowledges, have taken the factory productivity up compared to manual production. "One of our best-selling products, of which we make thousands every year, used to take 25 minutes to weld together. Now, with ABB robots, it takes less than four minutes," says Vestre.

"In 2025, we aim to be the largest street furniture supplier in Europe. We aim to be recognized as the most sustainable furniture brand in the world. And we don't want to move any manufacturing out of Scandinavia. By saying that we are going to be the biggest, greenest and still have manufacturing in high-cost countries, we have to think about productivity and invest in new technologies."

Building a business case for marine plastic waste
In parallel to running a sustainable business, Vestre is exploring other environmental initiatives, such as collaborating with the Norwegian research organization SINTEF on developing materials from ownerless ocean plastic waste.

"At Vestre, we don't use plastic in our manufacturing – all our products are based on metals and wood. But we are in this project because we want to promote and investigate the business opportunities it can offer," Vestre says.

The project, which has become a full-fledged company called Ogoori, looks into establishing value chains – collecting and recycling the plastic, making new products out of it, and leasing and tracing them to make sure they don't end up in the ocean 50 years from now.

"We have already done some tests at the SINTEF lab in Trondheim, and the quality of the recycled plastic is much better than we had hoped for," Vestre says. "We have some models printed out of 3D plastic, and the quality is very good. The material is very honest when it comes to color variations – you get what you put into it."

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We are testing out a new business model where we can return old and worn furniture to our factory, paint it, replace spare parts, make it look like new – and then sell, rent or lease it to a new project.

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Vestre factory in Torsby, Sweden

If the results continue to be promising, Vestre may consider using recycled ocean plastic in their own products: “It is also a question about product development – adding new materials and technologies.”

Setting a clean course
Evolution, or rather, revolution in technology is something Vestre believes can set not only industrial, but also developing countries on course for clean energy: “Why should they invest in fossil fuels when they can go directly to renewables? We can lift more people out of poverty, but do it in a sustainable way.”

That doesn’t, however, mean stopping economic growth: “I think it’s close to ridiculous to say we should end economic growth. If we tell the

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The Plus – Vestre factory to be built in Magnor, Norway

developing countries that they will not have the same life quality as us, we will never get them on board."

What Vestre advocates for is sharing economic growth and disconnecting it from the use of natural resources, had he is putting the company forward as an example: "We produce our own solar energy, we use trucks powered by the latest generation of bio fuel, and we hope to transition to electric trucks very soon. We source the greenest steel and aluminum in the world, and our factories are fossil-free." In 2019, the Vestre Group delivered growth of 20 percent and decreased their emissions by 10 percent, meaning that they are both growing and reducing their own emissions: "Exactly what I mean by disconnecting economic growth from the use of resources," Vestre confirms.

Another crucial aspect of their philosophy, Vestre says, is that ignoring the new generation that demands addressing climate change with concrete actions is no longer an option. The generation that environmental activist Greta Thunberg represents will be "extremely powerful in 5-10 years from now," he says. "They will be represented in all parliaments of the world, in all aspects of decision making. They don't compromise anymore."

The rise of a new generation of decision makers gives Vestre reason for optimism: "We will see major changes within five years, and people and companies that don't get it will not be in business five years from now. This is why we need new economic models – to be able to make the right decisions on a long-term basis."

In the end, Vestre believes, companies that lead the way in terms of sustainability will have happy customers. "They can also improve their profits. By running operations sustainably, they can save resources and energy, and use less materials, getting more out of what they invest as a result."

We aim to be recognized as the most sustainable furniture brand in the world.

Sustainable development and green growth shouldn't represent a threat, but rather a "huge business opportunity," Vestre says. It's a matter of perspective: "We can question if we have the courage to go in that direction, or see the business opportunities that this approach will open. That's how we think about it – amazing business opportunities, if you do things right."

Hydrogen fuel cells
To the Moon and beyond

Fuel cells have emerged as the best mobility solution to enable deep exploration of the surface of the Moon, and eventually Mars. ABB spoke to the Japan Aerospace Exploration Agency (JAXA) about its pioneering project to make the next generation of manned rovers a reality, in tandem with automotive giant Toyota.

Rover development team member Hiroki Furihata is a man on a mission. Speaking from JAXA headquarters at the Uchinoura Space Center in Kimotsuki in Kagoshima Prefecture, he says the countdown has begun and that if all goes according to plan, a flight model of the rover will be ready for Moon missions by 2029.

We want to extend trips to a total of 42 days or six weeks at a time.

Moving humans around with maximum efficiency and optimum safety is the key to sustainable space exploration. Together JAXA and Toyota have set their sights on developing an exploration vehicle that will be able to cover an unprecedented amount of ground. The partners signed a three-year joint research agreement in 2019 that will see engineers focus on manufacturing, testing, and evaluating various prototypes.

JAXA and Toyota break new ground
Featuring a pressurized cabin and powered by fuel-cell electric vehicle technology, the JAXA/Toyota rover will be light years ahead of the "Moon buggies" used in NASA's Apollo missions in the 1970s. Range back then was restricted by a "walkback limit", or the distance, in case of a failure, that an astronaut could safely manage on two feet to get back to the landing module.

"An open lunar buggy with extended range is great, but the crew would still have to wear space suits the whole time. It's difficult to stay suited up for any length of time, so trips would be limited to one

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Concept for the pressurized rover, jointly pursued by Toyota and JAXA

to three days," says Furihata. "We want to extend trips to a total of 42 days or six weeks at a time."

One tank goes a long way
Total driving time on the initial mission is expected to total more than 10,000 kilometers (6,213 miles). "The rover will need to cover that kind of distance to locate and study interesting scientific targets. A pressurized cabin is key to achieving this," Furihata says. Toyota's next-generation fuel cell to enable the rover to travel up to 1,000 kilometers on one tank of hydrogen.

Both hydrogen and solar were considered as energy sources. Together with Toyota engineers, JAXA concluded that a fuel cell powertrain is the most stable option, combining high energy density with lighter weight and compact size. As the team calculated the amount of energy that would be sufficient to secure the driving range required, they found that fuel cells were the best choice, at approximately one-fifth the mass of lithium-ion batteries and about 20 percent smaller in terms of volume. This highlights the superior performance capability of fuel cells being proven right now here on Earth. On the Moon, the water produced from the generation of electricity could be reused as either a coolant or as drinking water.

Driving at night

Extensive tradeoff evaluations were conducted to identify the best sustainable power source for the rover based on the defined exploration region at the moon's south pole, and driving distances. It will operate both during the day and at night – which on the Moon last for roughly two weeks each – as well as in freezing craters that even during daylight are permanently in shadow due to the low angle of the sun. "The lunar surface is also very variable, flat in some places and pretty rugged in others. You need power to negotiate that harsh terrain," says Furihata.

Furihata says other propulsion technologies could emerge in the future, but his view is that hydrogen will remain the best solution. "Research here on Earth is developing very rapidly. Space technology is cutting edge. Improvements in energy density and efficiency of the fuel cells will undoubtedly enable rovers to travel even greater distances."

According to preliminary parameters, the rover will measure six meters long, 5.2 meters wide, and 3.8 meters high – roughly the size of two minivans. The 13-cubic-meter cabin will have room enough for two astronauts. "Activity outside the rover will obviously require space suits. But when inside they won't have to wear them," says Furihata.

Fuel cells will undoubtedly enable rovers to travel even greater distances.

Auxiliary role for solar

The fuel cell will not only propel the rover, but also power all the electronic devices and human support systems on board. "We're still calculating how much energy eliminating the need for suits will require," Furihata says.

"Energy mass also clinched it for fuel cells in terms of transport. Given the significant mission energy requirement, using solar power would mean you'd have to carry all the solar photovoltaic panels with you. That's a lot of weight," Furihata says. However, the rover will be equipped with a deployable solar cell for charging onboard batteries during daylight, so ultimately there will be a combination of both power sources.

Using solar power would mean you'd have to carry all the solar photovoltaic panels with you. That's a lot of weight.

Astronomical autonomy

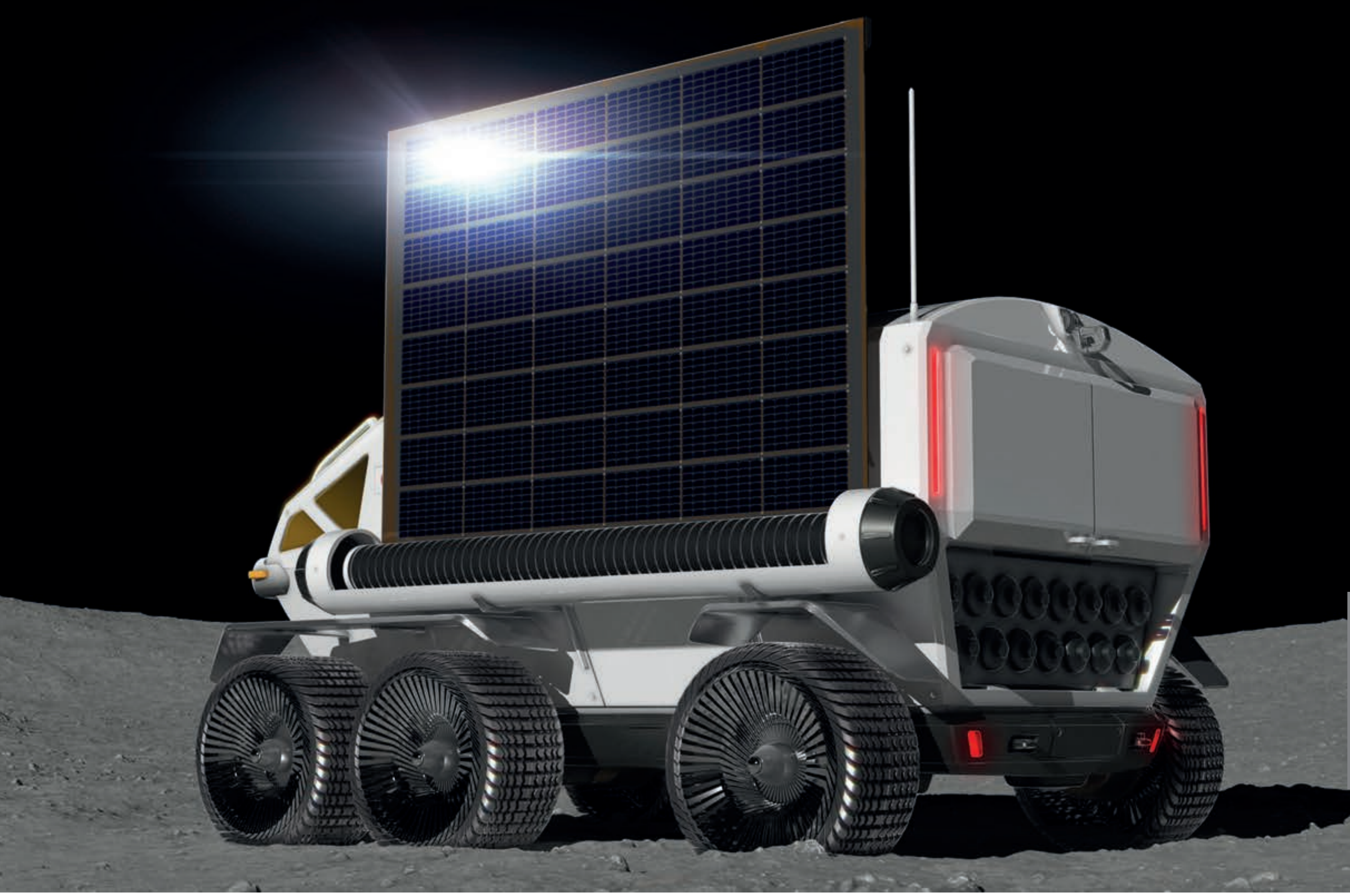
The rover will have fully autonomous driving capability using a sophisticated array of sensors, cameras, and LiDar (light detection and ranging) – in line with technology already being applied in land vehicles by Toyota and others, and by engineering companies like ABB for ships. The rover will be of course be enabled for remote operation from the landing craft and/or mission control on Earth, but this is inherently risky because of the time lag in transmitting signals to and from Earth. A self-driving function is an absolute necessity.

Furihata says the current operations scenario, at least initially, will see two rovers travelling in tandem. If something happens to one, the other is there to help. However, in the event of the astronauts being disabled, the rovers will be able to return to the landing craft under their own command.

Collaborative space

The International Space Station (ISS) and lunar exploration are the challenges that will drive development in all areas, including mobility. Then the big red planet. "Mars is our ultimate goal," said Furihata. "The Moon is our gateway, a stepping stone to future exploration."

The rover forms part of a wider international project also involving NASA. The US agency has been conducting its own infrastructure studies as part of its Artemis program, where the ultimate objective is to establish a human presence on the moon (dubbed "Gateway") as a springboard to deeper space. It plans to have humans back on the Moon as early as 2024. The idea of manned rovers as part of the mix is not new per se. A NASA study in 1990 examined the power requirements of such



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The rover will be equipped with a deployable solar cell

a vehicle for Mars missions, but the power pack under consideration back then was an on-board nuclear reactor. “We’re coordinating with NASA now and building on their experience. But we want to take it to a much more ambitious level,” Furihata said. “It has to be done sustainably.”

Strong starting lineup

Furihata says his team has seen a lot interest in the project from academia and industry in Japan. “We have Mitsubishi of course and other space-competent companies who’ve been involved in rocket development and the ISS. But the enthusiasm has spread to non-space enterprises, ranging from automotive components to domestic appliances. All of them have cutting-edge technologies that could theoretically be used on the rover. The interior space needs to be fitted out, so the hotel element is key.”

An enormous amount of work will have to be done before the rover´s 2029 completion date. “A decision to move forward with a full-scale prototype will be taken in spring of 2022. The next two years will be spent on acquiring and verifying data on the driving systems. The three years after that – from 2024 to 2027 – will be used to design, manufacture, and evaluate an engineering model,” Furihata says. That will be followed by design of a full-production variant with the necessary packaging to fit into a rocket. From 2027 the focus will be on performance and quality testing of the flight model.

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The Moon is our gateway, a stepping stone to future exploration.

No testing location for the rover has yet been decided. “We’ll coordinate with NASA and other international partners to determine the site. It might be elsewhere, but the baseline location is Japan,” says Furihata. It certainly promises to be an exciting project and one where Japan can demonstrate its tremendous capacity for innovation.

Electric, autonomous and efficient
Sea busses can fill a vital niche

Waterborne public transit is a natural solution for cities built around rivers, lakes and harbours. Add electricity and autonomy to the picture and you have Zeabuz, an on-demand aquatic bus system designed for operation on compact urban routes.

“Short-travel ferries will likely be the first application of autonomy in marine passenger transportation,” says Erik Dyrkoren, CEO of Zeabuz. “These systems are suited for most major cities that are built around navigable bodies of water, and that means most major cities in the world.”

A high degree of autonomy will improve efficiency and help make the system more easily accessible to the public.

Zeabuz is the latest marine transport innovation to come out of Norway. Blessed with the world’s second-longest coastline, Norwegians have a history of seeking solutions from the sea. But according to Dyrkoren, their fondness of advanced maritime technology is the main reason so many leading-edge initiatives are emerging from this long and narrow Nordic land.

“Norway is a very good place for developing autonomous marine systems right now,” he says. “History, geography, public policies, technology, and competence are all converging.”

Clean and simple

Electric power, autonomous charging and simplicity of operations are all essential components in the future success of Zeabuz, Dyrkoren claims. “Robust propulsion will be a central factor. Electric propulsion is the most dependable and requires the least intervention, and it will also help reduce emissions in the urban environment.” In addition, a high degree of autonomy will improve efficiency and help make the system more easily accessible to the public, he says.

Dyrkoren explains that Zeabuz will function much like an elevator in a building, with pre-set stops and on-demand service. The challenge lies in translating the constraints of elevator operations to a more fluid environment. “Existing rules do not accommodate the kind of solution we are proposing. Arriving at the right rules for operation will be critical to the success of the system.” Stipulations thus far include maximum 300 meters of transit and operation close to land, simplifying requirements for passenger safety: “Shorter transport legs simply mean there is less risk of accidents.”

He adds that short-travel, highly-automated ferries place less demand on seafaring skills than larger crafts sailing the oceans. “The necessary backup is also easily accessible from shore, including emergency services.” The system will not be one hundred percent autonomous, Dyrkoren says, but will employ the ‘human in the loop’ principle, involving remote monitoring and operations.

High-powered hometown

Founded by a group of professors from the Norwegian University of Science and Technology (NTNU) in December of 2019, the Zeabuz team recruited Dyrkoren in early 2020 from his post at the helm of BlueEye Robotics, a Norwegian maker of remote controlled underwater drones.

Dyrkoren relates that virtually every component needed to build Zeabuz can be designed and manufactured in close proximity to their headquarters in Trondheim, located on Norway's central coast. "We have turnkey suppliers of systems and

We plan to use off-the-shelf technology wherever possible, but in this community that also means cutting edge technology.

subsystems, and they are constantly revealing new developments in marine autonomy." Adding to the potent local mix is NTNU, with more than a decade of research on autonomous systems.

Zeabuz technology is derived from well-proven products like dynamic positioning, where market Norway has been a world leader since the 1990s. "We can use the same basic algorithms and power technology. We plan to use off-the-shelf technology wherever possible, but in this community that also means cutting edge technology."

Moving fast to meet the future

The Zeabuz concept can be deployed relatively quickly, Dyrkoren says: "There are other marine transit projects currently under consideration around the world, but they have fairly long time frames. This could be done much faster." The company's ambition is to have an operational pilot within two years. "The market will determine the pace of progress after that," Dyrkoren adds. He reports that a prototype is currently under construction, including both vessels and docks.

The future mosaic of sustainable transportation will contain many pieces, and the urban sea bus is likely to be one of them. For now, Dyrkoren's first priority is getting a pilot project on the market. As good as Norway is on marine autonomous solutions, he acknowledges that Zeabuz must move fast to keep ahead of fierce competition: "The project is up to the challenge. We have a high-powered team with clear goals, and we can generate a lot of energy once we get up to speed."

Electric planes
Prepare for takeoff

Electric flight is coming. The first commercial electric flights are anticipated as soon 2030, and this would appear to be one of those enthusiastic forecasts that is likely to come true.

In all corners of the world tinkerers and titans of industry are working their way toward the dream of powered flight without fuel. Tomas Brødreskift, CEO and co-founder of Equator Aircraft Norway, subscribes to the 10-year scenario for the first commercial electric powered passenger flight.

"The pace at which technology is progressing is amazing. We must find emission-free solutions for transportation, including flight, and this will drive exponential development in electric and green propulsion," Brødreskift predicts. "For us, it is both exciting and frustrating. We know it is coming, but it's hard to develop a strategy when things are moving so quickly."

Not that this unpredictability is dampening Tomas Brødreskift's optimism. "Recently I attended Europe's biggest small plane exhibition, with a 4,000 square meter exhibition hall dedicated to electric planes. The push is already strong, and the shift is being discussed everywhere," he says. "Political pressure is driving development. Governments are pushing agencies to adapt more quickly as people demand more sustainable air travel." This, he believes, represents the tipping point for electric flight: "This is a freight train that is not stopping. You can either get on board and adapt or get left behind."

Fitting the pieces together

Brødreskift picked up the thread of zero-emission flight from a German visionary, and is advancing it on the runways, and waterways, of rural Norway. He says his devotion to aircraft design started as a 27-year-old student of industrial design, when he met Günther Pöschel, the founder of Equator Aircraft Company in Germany.

Pöschel built three different aircraft prototypes from 1969 to 1985 using composite construction. Composites were lighter than steel or aluminum, opening the door to alternative propulsion, though that would come later in Equator's history. "He did not experiment with propulsion, but rather with materials and aerodynamics," says Brødreskift. "This initially sparked my deep interest in making a highly efficient aircraft."

The first concept back in 2009 was in fact not electric. "We started out looking for alternative combustion solutions," Brødreskift tells. "We also wanted to focus on the sports plane market, instead of reviving Günther's designs for six-to-eight seat aircraft."

For Equator, that meant seaplanes. But as Brødreskift says, "Any seaplane is a compromise. Historically, you ended up with a bad boat, and a bad airplane." Guided by their vision of versatility, Equator set out to strike the right balance.

"When we revived the composite designs in 2010, electric propulsion was new. Some gliders were using it, but only to achieve altitude or in emergencies," Brødreskift relates. In fact, Equator landed first on a hybrid solution: "We needed the extra power to get off the water, and we envisioned an

electric-combustion hybrid. We were essentially designing the plane around a fantasy power plant."

Their search for a suitable power solution led them to one of the first manufacturers to deliver electric power solutions to aviation. "Once we saw that there were opportunities, we got more interested in electric propulsion and began to conceptualize a plane around an electric motor." Equator eventually managed to collect enough private and soft funding to start developing their own hybrid drive train. "This included a 100kW electric machine, batteries and a combustion range extender. We are currently flying this system, although on pure electric power in the initial phases of the test program," says Brødreskrift.

The evolution of electric
Like other industries, aviation is benefitting from rapid developments in battery technology. "Batteries are so much better than just a few years ago, and technologies are making everything lighter, so our focus is shifting from range extender combustion motors in a hybrid solution to working more on extended battery flight."

Electric flight is becoming doable for even a small company, Brødreskift says, but certification of electric propulsion for aircrafts remains difficult, both financially and time-wise. "We are hoping for at least one certified propulsion product from the major manufacturers. If we had off-the-shelf engines, we could focus on developing airframes, but so far this has not happened. For us, that makes it a waiting game. In the meantime, we have our internally developed system."

The confluence of industry players offers hope though: "Mergers and collaborative efforts should accelerate the process somewhat. Though their focus will be on heavy aircraft first, we're excited to see where all the work put in by these players will lead."

Just add water?
With the many hurdles already in the way of electric flight and composite airframes, some might question the logic of adding water to the mix. Brødreskift's reply is neatly pragmatic: "Landing on water gives added flexibility for access. The water landing alternative is an obvious advantage in an emergency, but it can also be nice to

go wherever you want to go if you are flying over wilderness areas or along the coast."

Reviewing the business case for amphibious aircraft, Brødreskift reports that today's float planes have three to four times the accident rate of land planes, and the fleet is ageing and needs to be renewed. "The market could grow if planes were cheaper to operate, safer and more flexible."

He adds that 70-80 percent of major cities are located adjacent to water, making downtown-to-downtown routes using seaplanes potentially attractive. "Noise is the main restricting factor in cities, and electric takeoff and landing would be virtually silent. If a company can make good commercial mobility solutions for accessing populations through air and sea, we believe the business opportunities could be significant."

The smart way forward

There are a few likely scenarios for breaking into the market, Brødreskift says. "Flight schools use two-seaters for training. They would require one hour of noise-free and affordable flight in order to practice takeoffs and landings in locations close to urban areas. This should happen within five years." For now, Equator's focus is on the next phase of potential business models, with electric aviation as a means of transport. "There are already quite a few routes of less than 30 minutes that could potentially be electrified."

> Noise is the main restricting factor in cities, and electric takeoff and landing would be virtually silent.

Larger aircraft will also be tried out in the same period, he says. "Airbus and others will gain valuable data to guide decisions for future, starting with seating capacity of anywhere from 10 to 19. The challenge for us is being able to share in the knowledge that these companies are acquiring."

Brødreskift believes that the first companies to market will be those that adapt conventional solutions, ensuring a smoother approach to certification. "Radical innovations will only prolong the certification process. In this respect, we are taking a more pragmatic approach to building both new airframes and propulsion systems. We believe this is a better long-term solution, as aircraft in general and the technology currently in use are ripe for renewal."

Batteries in the big picture
On the right track for recycling?

Batteries are being deployed at full speed across all segments of the consumer and industrial markets. To get a perspective on the big picture for battery footprint, Generations spoke with Hans Eric Melin, Managing Director of Circular Energy Storage, a London-based lithium-ion battery lifecycle consultancy.

Asked whether global society is currently following a plan for responsible production, use and disposal or recycling of batteries, Melin has a layered response: “That depends on who you ask,” he says. “In the automotive industry, the debate is raging on the overall battery footprint. Sustainability is being used as an argument against car batteries, but this is coming from those with competing technologies. Lithium-ion batteries (LI) were not an issue for phones and laptops, not least due to their small size, but in cars they are much bigger, and they threaten other technologies.”

In the automotive industry, the debate is raging on the overall battery footprint.

He reminds that LI is still an emerging technology whose trajectory is yet to be defined: “LI batteries enabled the mobile phone segment, and that helped grow the overall LI industry, which then moved into the auto industry.” Now he notes that the scale of LI in the automobile industry is encouraging other industries, including marine.

“There has been dramatic development over the last 20 years. Batteries are being manufactured differently now, and on a huge scale compared to five years ago.” Scale is important for the overall CO_2 footprint of LI battery production, he says. “Here, it’s really ‘The bigger the better’.”

Battery recycling at scale

Melin points out that LI battery recycling has been done from the start, but is still often described as non-existent. “That is largely because the countries controlling that narrative are not recycling much,” he explains. “Consumer electronics are exported from these countries, primarily in Europe and North America, for reuse and recycling, mainly to Asia, and mostly to China.”

He notes that China now has two-thirds of the world’s LI battery production, and that recycling is an important part of production there. “The best possibilities for recycling are present where batteries are produced at scale. A country must produce batteries in order to be efficient at recycling.”

Regarding the role of legislation in battery recycling, Melin defers to market forces: “Legislation does provide some guidelines, particularly laws that require companies to take batteries back at the end of their lives, but if and when recycling volumes meet demand, we won’t really need a grand plan.”

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Hans Eric Melin
Managing Director
Circular Energy Storage

Other industries: the same, but different
Looking to other industries with mature lifecycle perspectives, such as aluminum, how does Melin compare the battery industry in its thinking? “The battery industry is fairly comparable to aluminum, but recycling batteries is more complex. There are many more elements to be dealt with, and the cost level is higher.”

Aluminum requires huge amounts of energy to produce, he says, so stakeholders need to recoup investments through reuse of produced material. “This is not the same with battery manufacturing. Most of the manufacturing energy is spent applying cathodes to current conductors. Recycling does not remove this part of the process from manufacturing.”

Recycling applies mostly to materials, he elaborates. Here, mining practices can be made more sustainable by using hydropower for mining operations, and gas rather than coal to power operations. “Companies building efficient value chains are in a good position, but achieving positive value is not possible along all recycling value chains. At some point someone is going to have to pay something.”

Who is getting it right?
“Europe has a history of waste handling and management more than recycling,” Melin observes. “They have been dealing with nickel cadmium and heavy metals for some time, but more as waste than in a recycling perspective.” Yet there are some expectations for recycling in Europe, he says: “The infrastructure is not the most efficient, but it is perhaps realistic given market volumes.”

Parallel to this, recycling startups are emerging around the globe, he says. “We get new calls every week from interested parties, especially in Southeast Asia,” Melin reports. “Their advantage is proximity to China.” Growing battery production in Europe will help grow the recycling market, as manufacturers will have possibility to connect recycling to production. “This is true also in the US,” he adds. “The real question is who will produce the most batteries. That is where the most efficient recycling will be.”

Second life is another growing option, he says. “China is also excelling at second life products. It is simply not the case that batteries are being dumped. As long as there is value in products, they will be reused. This is part of the global interconnected economy.”

Does Melin believe the world will ever see a truly circular battery economy, and if so, when? “We are very close today,” he believes. “Few products are as circular as the LI battery right now, but we need a good product to start with. Car batteries are so good that they can have a second life, and the product is recycled too.” Not least, Melin points out that very few LI batteries have reached the end of their lives. “LI batteries have a long lifetime. The ability to reuse and repurpose LI batteries is there, and it is happening today.”

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North American perspective: A new maritime era

The next steps to a new maritime future

The era beyond carbon-fuelled, manually operated ships is beginning to take shape. As with all major transitions, this shift to a new normal will consist of many steps along the way, taken over time. At this pivotal point in the history of shipping, ABB Marine & Ports invited leading voices from the North American maritime community to New York for a roundtable discussion of the passage into a new age of electric, digital and connected vessels, increasingly autonomous, and powered by sustainable means.

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Note: The discussion took place in December 2019, prior to the outbreak of the global coronavirus pandemic.

Mission zero
Quitting carbon

Responding to growing climatic and regulatory pressures, the shipping industry is on a mission to phase out fossil fuels. Against this backdrop, leading voices from the North American maritime community discuss the rules and rewards that can be applied to help and hurry industry stakeholders along the way to a zero-carbon future.

Welcoming the guests, Rune Braastad, SVP, Division Manager at ABB Marine & Ports U.S., noted that shipping is in transition, with both stricter regulations and new technologies driving change. “The pace of change is faster than ever. Vision is important in times like these, but realistic goals and stepwise progress are the way to ensure sustainable development.”

On the regulatory front, the International Maritime Organization (IMO) has called for a 50 percent reduction of GHG emissions by 2050 compared with a 2008 baseline, and for phasing them out as soon as possible in this century. Carbon intensity is to be reduced by 40 percent by 2030, and 70 percent by 2050.

The first steps toward compliance

Moderator John Snyder opened the floor to discussion starting with the IMO 2020 sulphur cap, the first major piece of emissions legislation to impact the industry.

Anshul Tuteja, Associate VP, Global Fleet Optimization, Royal Caribbean Cruises Ltd. (RCCL), expressed the urgency shared by his colleagues in the room: “The clock is definitely ticking on emissions now. We began installing scrubbers four years ago, with about half a billion USD invested to date.” But no such major decision is without its complications, he confirmed. “These are challenging times in many ways. Luckily, we went for hybrid scrubbers, so we have the option to comply with stricter requirements. But there is a learning process involved.”

> The clock is definitely ticking on emissions now.

As an example, he cited unsightly steam plume caused by the moisture added to exhaust by the scrubbing process, requiring ships to run on cleaner fuel despite having scrubbers installed. Though he acknowledges that alternative fuels have their advantages, Tuteja said RCCL remains at peace with their decision: “Right now we see an economic advantage with scrubbers.”

While RCCL will take delivery of three 5,000-passenger ‘Icon Class’ cruise ships powered by liquefied natural gas (LNG) between 2022 and 2025, Tuteja noted that as a fossil fuel, albeit significantly cleaner than oil-based fuels, LNG would remain an intermediate solution to emissions reductions.

Derek Novak, Chief Engineer at the American Bureau of Shipping (ABS), reported that he sees

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Rune Braastad
SVP
Division Manager
ABB Marine & Ports U.S.

the bulk of their clients implementing a variety of strategies. "Scrubbers are installed on 15 percent of all ABS Classed ocean-going vessels, many of these with open loop. We see a learning curve on the operation of scrubbers, but most of the issues can be resolved by applying some best practices. There have been some technical issues with installations, and some system failures, but the operations of these systems are not very complicated. We do expect more feedback as we go along though," he noted.

Solutions for the shift

Capt. James C. DeSimone, COO of Staten Island Ferry, is seeing decisions driven by fuel availability: "Many shipowners think heavy fuel will not be readily available in the future, so they are not investing in scrubbers."

Jennifer States, Director for Blue Economy at DNV GL and Project Director for Washington Maritime Blue, observed that lighter fuel seemed to be emerging as the more popular solution, with fewer scrubbers installed than had been predicted. Noting that initial estimates predicted around 4,000 ships operating with exhaust gas cleaning systems by 2020, she confirmed that about 2,800 vessels had been fitted with scrubbers by year-end 2019.

Neither path is without challenges, noted Michael Carter, Acting Associate Administrator for Environment and Compliance in the US Maritime Administration (MARAD): "There are issues with burning fuel other than what an engine was designed for, including insufficient lubrication, excess wear, and so on. With scrubbers, the catalysts used to remove sulphur from exhaust can leave particulate matter, and managing that waste is a challenge."

Snyder pointed out that companies operating in the U.S. have to comply with Environmental Protection Agency's Tier 4 emissions regulations, and asked how this requirement would influence the operational and design strategies for U.S. owners and operators.

“We are typically docking in heart of a city, so we are required to comply with Tier 6,” Tuteja responded. “We are aggressively pursuing solutions for that. Scrubbers and selective catalytic reactors are options for port stays and maneuvering in harbors, and we are retrofitting to accommodate shore power. Moreover, we see these as good contributions to cleaner air, regardless of requirements.”

Braastad added that many vessels are being fitted for shore power, but land power installations are not following suit. “What will operators do if this pattern continues?” he asked.

“We know that Port Everglades has looked into shore power costs, but USD 25 million per berth is a big investment for a limited number of customers,” Tuteja offered. He added that each cruise ship would require as much as 5-10 MW of power while berthed, a major drain even for a large port like Miami. “Norway is taking a leading role on shore power, as is California. But it is important to look at where ports get their power. Gas and coal generation is getting cleaner, making them more attractive, but even cleaner energy upstream is the long-term answer.”

States pointed out the importance of planning in the implementation of shore power. “Utilities are saying that the business case does not always make sense. With relatively few ships using shore power seasonally, there may not be enough utilization to payoff infrastructure costs. Now is when we need to get everyone working together to find out how to better plan and recoup investments. Energy planning cooperation needs to go broader, to bring stakeholders together to meet future needs. California has said it wants to impose cold ironing for all ships, but this may need to be followed up by complementary measures to balance out the financial burden.”

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Jennifer States
Director
Blue Economy
DNV GL

Project Director
Washington Maritime Blue

Fuel in different forms
Jostein Bogen, Vice President, Global Product Manager Energy Storage & Fuel Cells, asked whether fuel cells could provide solutions on ships and on shore.

“We are looking at hybrid systems for our ships. In fact, we are doing a fuel cell study,” Tuteja replied. “We also developed a prototype with ABB and Ballard Power Systems. Storing hydrogen on board a vessel carrying passengers is still a hurdle we need to address, though.”

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Norway is taking a leading role on shore power, as is California.

Carter said that onshore installation is also being considered as an option for fuel cells. “The Department of Energy is looking at how to electrify ports using fuel cells. These measures would offset other emissions. They are looking into applications for hydrogen in the maritime space. The harbor workboat fleet and other users could potentially be added to the mix.”

States mentioned electrolysis technology suppliers looking at moving into the maritime sphere. “This is a good opportunity for many suppliers with established business in other industries,” she said, adding that clean hydropower in Washington State gives local companies a natural advantage. States helped to head up a regional Maritime Blue forum designed to bring such players together. “We are looking to establish a maritime R&D agenda for hydrogen, batteries and alternative fuels, but first we need to identify the maritime industry’s needs. By getting stakeholders to come together and tell us their needs, we can start to create the pipeline for solutions.”

Opinion, authority or economy: which is more powerful?
The participants were asked whether public opinion was becoming a major influence on stakeholder choices.

“It is more the local authorities that are driving change,” Tuteja replied, though conceding that youth activism and the public awareness on climate change are shifting opinions. “The first question in Scandinavia is now about the environment, and this is driven by the strong public sentiment. I think the rest of the EU is also feeling the same pressure.”

Ole-Jacob Irgens, Global Sales Manager, Propulsion Solutions at ABB Marine & Ports, responded: “I think over the past few years the light bulb is going on over peoples’ heads. There is a definite acceleration of initiatives in more market areas, but awareness is still growing gradually.”

Novak agreed, noting that container ships were being rated for emissions, but not yet garnering the same attention as the cruise segment. States concurred that while public attention to the cargo segment remains relatively limited, consumers are certainly becoming more aware of the impact of their purchases.

Bradley Golden, professor at Webb Institute, confirmed that the general public is seeing global shipping as more of a concern. “Shipping is still the most efficient way to move goods, but Emission Control Areas’ and IMO regulations are gaining momentum. Relative emissions are small, but they are being increasingly challenged. All global shipping is being pressured to clean up.”

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Now is when we need to get everyone working together to find out how to better plan and recoup investments.

States noted that despite the growing impact of regulations, shipping’s ultimate motivation to change may be financial. “Bonds and other finance solutions are becoming key drivers. The question for the future is, will the banks support shipping that is not green?” She cited the Poseidon Principles, under which major shipping banks will for the first time integrate climate change considerations into their lending decisions in order to push shipping toward decarbonization. “Investments won’t be made unless owners have future-proof plans for their vessels,” she said.

Snyder noted that emissions have become a major factor in the offshore support market. "The oil companies are very aware of pressure from investors to show reduced emissions, and ship operators want to be more attractive on the charter market. They are using digital technology, monitoring, and more efficient logistics to clean up. Is the pressure in the freight segments coming from cargo owners in the same way?"

Novak offered that the primary pressure for now is coming from regulators, but to a growing degree from cargo owners.

"In any case we cannot do it all by ourselves," Tuteja said. "OEMs, class, academia, and owners all have to be involved. It starts with prototyping and learning. We are all obliged to do the right thing, but our actions have to balance with our economy, and provide sustainability."

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Energy planning cooperation needs to go broader, to bring stakeholders together.

Seeking stability in times of change
Braastad acknowledged that rapidly evolving regulations present challenges to shipowners: "How can a shipowner in this environment plan for a newbuild that will last for more than 30 years?"

"A decision on fuel will last the life of the ship," Tuteja acknowledged. "This is why energy efficiency has become the new guideline. Each new class of vessels will be better than last. Carbon neutral is the ultimate goal, but eventually it will become too complex to clean carbon fuel. In the long term I think we will have to shift our focus to alternative fuels. For example, where we have moved to LNG technology we are already looking at how to transition to green LNG. The same process applies to biofuels and synthetic fuels."

Ethan Wiseman, Assistant VP, Fleet Manager at NYC Ferry, NYCEDC, maintains that the new reality demands addressing the dual challenges of decarbonizing as much as possible while still meeting market demands. "There is no single solution that fits all needs. Different routes will have to be found to meet different needs." For example, he acknowledges that while Tier 4 is not reachable for all vessels, newer ships that able to comply will fill in the gap.

"We have three new Tier 4 vessels, so we are moving in the right direction" offered DeSimone. "But public ferry operators are subject to public opinion. We can examine available technologies and figure out which risks can we take, but we are obliged to meet public requirements. We cannot use passenger ferries as experimental projects. The technology has to be reliable and proven before we can embrace it."

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John Snyder
Editor
LNG World Shipping
Offshore Support Journal

Michael Carter
Acting Associate
Administrator
Environment and
Compliance
MARAD

While Denmark and Norway have provided federal mandates to implement new propulsion technologies on passenger ferries, the State of New York has not gone as far, he observed. “Under the present circumstances we cannot rely on experimental technologies for primary service.” Looking forward he noted that moves from the IMO toward 2050 will likely open more doors. “More vessels with new solutions will be operating by then, and we will have more experience to draw on. Electric power is looking more like safe bet, and this could become our prime mover over time.”

States emphasized that the Washington State Ferries decision to go with electric hybrid solutions provided a noteworthy example for the industry: “The Governor has provided a great example of what a state can achieve by declaring for this option, but the existing regulations are not always aligned with implementing the new technologies. An even stronger signal would be to craft regulations to encourage or promote emissions reductions with even greater predictability and support. Regulations can guide the market in the right direction if they are realistic and robust.”

Fuelling the future of shipping

Ships will continue to carry the bulk of global trade into the foreseeable future, but traditional fuels must be phased to meet strict sustainability goals. Maritime industry leaders gathered to reflect on future solutions for the ships that fuel the global economy.

Framing the discussion was the recent International Maritime Organization's call for a 50 percent reduction of greenhouse gas emissions by 2050 compared with a 2008 baseline, and for phasing them out as soon as possible in this century. Carbon intensity in shipping is to be reduced by 40 percent by 2030, and 70 percent by 2050. In his opening query to participants, moderator John Snyder addressed the fundamental capability of the industry to meet these ambitious goals: "Is the technology available to get us to a zero-emission future?"

Good things are happening, but everyone needs to know how to get involved.

Optimizing options: a complex equation
"As we see it, there is no single technology as of today that will get us to zero emissions," related Anshul Tuteja, Associate VP, Global Fleet Optimization, Royal Caribbean Cruises Ltd. (RCCL). Scaling is the fundamental issue when faced with a number of options, he continued: "What is the investment required for each technology? Technology leaders need to invest as well, not just operators, and we need government support in the mix."

Michael Carter, Acting Associate Administrator for Environment and Compliance in the U.S. Department of Maritime Administration (MARAD), cited the examples of California and Washington State, both taking steps to support the green shift, including looking for partnerships.

In this setting, international partnerships become more important, he maintained. "Why should the players use time and resources reinventing the wheel? Go ahead and do some tests and then share the results. Good things are happening, but everyone needs to know how to get involved."

Edward Schwarz, Vice President Sales, ABB Marine & Ports US, pointed to the contradiction in distribution of new technology in the markets. "We have seen a polarization between established and developing segments emerging in the U.S. Why is this?"

Derek Novak, Chief Engineer at the American Bureau of Shipping, offered the power of the bottom line as explanation: "I think a lot of it comes down to economics. Not all nations are funding developments, and the shipping industry is still recovering from past crises. There is just not a lot of capital to be invested. And it should also be mentioned that emissions compliance measures like scrubbers are taking much of the energy in the market right now. This makes it difficult to prioritize development of batteries or alternative fuels in the way we otherwise might have."

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Ole-Jacob Irgens
Global Sales Manager
PG Propulsion Solutions
ABB Marine & Ports


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Ole-Jacob Irgens

Ole-Jacob Irgens, Global Sales Manager, Propulsion Systems, ABB Marine & Ports, pointed out that lifecycle costs also drive decisions on ship propulsion.

“Green is more expensive, yes, but not exponentially,” Schwarz replied. “What is really keeping our industry from embracing green solutions? Is the problem with regulations? Are there too many players? Why does the maritime industry compete at the bottom of the price range compared to other industries?” he asked.

“I think there is a fundamental mechanism at work in finding the business trade-off,” said Novak. “For example, batteries will be a supplement in most cases, not a primary power source. We can use technology to offset expenses and emissions, but if the dollars do not back up the case, no one will make bold moves on technology.”

Building the case for electrification

Jennifer States, Director for Blue Economy at DNV GL and Project Director for Washington Maritime Blue, noted that the government-led initiative to electrify Washington State Ferries is beginning to have an impact further down the supply chain. “Seattle was already supporting electrification before the decision from WA State Ferries to go with electric hybrid was made, but the industry side was not as far along in the process. Now we are starting to see companies locate to Washington to be a part of this effort,” she said.

“We are beginning to learn from other places as well. The charging infrastructure is still tricky. What is the impact on the grid? Operators shore power requirements need to be addressed together with the utilities and grid operators. There are lots of lessons to be learned, and needs are different onboard versus onshore.”

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Catherine Hale
East Coast Representative
Systems Engineer
Elliott Bay Design Group
Seattle

Catherine Hale, East Coast Representative and Systems Engineer at Elliott Bay Design Group of Seattle, noted: "EBDG is actively involved in eco-friendly vessel design including the design of fuel-efficient hybrid vessels. Although hybrid-electric propulsion will have higher initial installation costs, it can significantly reduce emissions and fuel consumption. A route profile is critical. All vessels and operators are unique, understanding key motivators that drive decisions (economical, costs, green, cutting-edge technology) is key to a successful project."

Green is more expensive, yes, but not exponentially.

States questioned whether investments in new technologies could be recouped by market demand alone. "Resiliency is also needed in the market. Can these new solutions be used to meet other needs beyond port or maritime applications? For example, could we see battery barges or barge-based fuel cell systems serving in multiple locations in emergency situations?"

The new energy mix

Jostein Bogen, Vice President, Global Product Manager Energy Storage & Fuel Cells at ABB Marine & Ports, pointed out that although batteries are gaining traction in many applications, they will not provide an answer for all. "Fuel cells using hydrogen are being investigated in many different applications. Not all hydrogen is green right now, but we see this as doable in the near future, especially for short sea shipping. We need hydrogen to produce methane and ammonia too, so there could be many sustainable roles for green hydrogen."

Hydrogen is on its way to establishing a wider footprint, Carter confirmed. "The Department of Energy has been working on potential hydrogen applications for many years. Containerized solutions are showing promise, and the same fuel cell solutions can be used to provide shore power using hydrogen."

Despite progress in alternative power sources, the bulk of work remains ahead, Carter maintained. "There is no silver bullet. We will need to fit the pieces together for each situation. Even in one harbour, vessels have different operating profiles that require different solutions. Also, given the significant capital costs of new technologies, change takes time in the maritime industry. So identifying and demonstrating alternatives now allows the industry to plan ahead."

The role of alternative fuels

While batteries and fuel cells hold great promise in the longer term, internal combustion engines dominate marine propulsion and will continue to play a central role for decades to come, demanding alternative fuel solutions. Paul Benecki, Staff Writer for The Maritime Executive, queried the group on the business case for liquefied natural gas (LNG).

Tuteja began with bottom-line reasoning: "Prices for MGO (marine gasoil) and LNG are basically same right now, but the gap between HFO (heavy fuel oil) and lighter fuels remains large. Where LNG will go in price is uncertain, and that will influence thinking."

Carter reported that when they investigated LNG options about four to five years ago, the cost difference compared to oil was significant. "When that changed in favour of LNG, it made the case more interesting. We still see certain storage and emissions issues, but the technology and market continue to evolve.

At the same time fuel options are becoming more flexible, he observed. "Biofuels are becoming more attractive, but there are still unresolved issues with quantity, price and infrastructure." Issues aside, he pointed out that a viable infrastructure for biofuels is needed. "The Department of Energy, the Department of Defense and we have invested in biofuels research, testing and demonstration for maritime applications, but the current market does not appear to support its widespread application yet."

Insurance is a factor in this development as well, he pointed out. "A lot of players are still wary of hydrogen, and even LNG. We need more and stronger standards in order to reassure those with doubts. For this we can look to leaders other places where progress has come further. We want to see global solutions for alternative fuels, but there is only so much we can do with each fuel. Each one is feasible in its own right, and they need to be applied to the situation where they are best suited."

Arenas for future solutions

"We believe that evaluating and demonstrating a variety of technologies and alternative fuels continues to be key to providing an array of options to the maritime industry. We have been able to use our own vessels and school ships as platforms for those kinds of projects. We hope to continue to do so," Carter continued. "MARAD is dedicated to assist the maritime industry in these areas if they are interested, and we are keen to share our own results with the industry. Partnering and sharing benefits all parties, and the opportunities are there."

Bradley Golden, professor at Webb Institute, agreed that the arguments for pursuing options outweigh the obstacles. "This is a reactionary industry, not proactive, and everyone remembers the mistakes that have been made. Alternative fuels will still have emissions, so we need to compensate for this. Batteries also have issues, even going back to the manufacturing process. We might be 'damned if we do, damned if we don't', but we need to keep looking and trying to find the best options for the future."

Although hybrid-electric propulsion will have higher initial installation costs, it can significantly reduce emissions.

He urged the industry to use academia to help them explore the most promising options. "The institutions are eager to learn more about future fuels and how they can influence change. Every college is looking for research opportunities, and unlike businesses with safety or commercial obligations, we can take chances. The universities can play a role, and they can work with anyone, including owners, governments, and original equipment manufacturers."

Carter confirmed that MARAD is working to get maritime schools and students involved. "Students are good at finding solutions, partly because they are open to unexpected solutions. We would definitely like to see more effort focused on maritime specific challenges and engaging our future mariners in finding solutions."

States noted that the entire maritime ecosystem should be at the table when new solutions are being discussed. "This is an issue of workforce development too. Right now we are struggling to fill maritime jobs. Getting these opportunities out and known would influence career choices. Sustainability is a key element in the thinking of the younger generation, and collaboration is essential in informing them of these opportunities. We can also use these collaborative arenas to build more long-term relationships. It's amazing how people open up when they are faced with a common task."

Learning by sharing

"Sometimes all that is needed is awareness of projects in need of support," Golden offered. "Some may not even require that much support. For many initiatives, it is more about sharing ideas." Carter agreed: "The Department of Energy is interested in maritime energy investments, and we can all do more to share information about relevant projects."

Tuteja highlighted the importance of gathering the knowledge of all invested parties into a common space. "The IMO Global Industry Alliance is a good arena for this. If we find fuel options that have worked for us, we contribute it to the common pool." The fundamental question is how to build better partnerships and share the burden of mutual challenges, he added.

"We recently participated in a project on battery safety that brought all stakeholders together," Carter reported. "We found that none of these had talked together at one time before. Getting them together as a group made a big difference. If industry players do not share, we are not going to find the right solutions."

Christopher Glynn, President of Maid of the Mist, the operator ferrying tourists to the foot of Niagara Falls, shared the learning process behind their decision to invest in an all-electric fleet.

"Given our close association with hydropower at the falls, when it came time to renew the fleet, we wanted to consider electric propulsion."

To familiarize himself with the available options, Glynn attended a conference on electric and hybrid marine propulsion technologies in Amsterdam in 2018. "Basically, I listened and learned. That conference opened my eyes to the attractiveness of electric propulsion."

Once the decision to go electric was made, their primary inspiration came from the Ampere electric ferry project in Norway: "There were strong parallels in our respective operations, not least in the charging cycles." Propulsion experts subsequently assured Glynn and his team that they could get the output they needed from batteries. "In fact we have never been large fuel consumers," Glynn acknowledged. "We spend more on raincoats than we do on fuel."

Rallying all resources

"Even though the public is pushing for a green power shift, the smaller companies are working for the bigger players, and they cannot take a chance on failing and letting their customers down," Hale said, receiving support from Novak: "The big players, including the oil and energy majors, need to help out further down the supply chain, but they are dependent on viable solutions."

Carter asked to what degree lack of proof might be to blame for lagging commitments to green solutions. "Can we really expect investments in unproven technologies?" He noted that not all stakeholders possess the resources necessary in order to produce the required verification.

In reply, Golden again encouraged the participants to entrust knowledge institutions with a central role in steepening the learning curve: "Academia can help to put all the information together, as long as we are not sharing secrets. Remember that students are the designers of the future. They could gain valuable experience and perspectives and take this knowledge on to the maritime industries. I think the key to assuring robust development is to take full advantage of all the options available to us."

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Jostein Bogen
Vice President
Global Product Manager
Energy Storage & Fuel Cells
ABB Marine & Ports

The steps to autonomy
Safety first

In only a few years, the discussion of autonomy in shipping has matured from headline-grabbing visions to pragmatic realism. Stakeholders now generally agree that autonomy will not be implemented in a grand sweep, but rather by increments. Then the question becomes one of priorities: what should be the first benefits realized through the stepwise implementation of autonomous technologies?

Efficiency, sustainability and profitability are all plausible answers to this question, but the discussion around the table at the ABB Marine & Ports gathering of maritime experts and authorities in New York last December pointed repeatedly to one primary conclusion: safety.

Autonomy is not just about saving money on crew or equipment, but about enhancing safety.

Invited to kick off the discussion, Allan Krogsgaard, Director of Business Development at classification society DNV GL, set the stage by acknowledging that it will be several years before the advent of commercial, fully automated vessels. "For now, we are still discussing different levels of autonomy and how they could be applied."

Introducing the theme of 'safety first', Krogsgaard noted: "Autonomy is not just about saving money on crew or equipment, but about enhancing safety. For example, giving seafarers more rest, or keeping them from having to enter enclosed or hazardous spaces. DNV GL wants to be on the leading edge of applying this technology, but it has to be about more than just helping companies grow their profits. Safety and quality must stay in focus."

Michael Carter, Acting Associate Administrator for Environment and Compliance in the U.S. Maritime Administration (MARAD) agreed that autonomous or data driven systems have a place in assisting the mariners to do their jobs, but the mariner still remains key.

First steps first

With the industry taking a step back from sweeping scenarios, moderator John Snyder, Editor of LNG World Shipping and Editor of Offshore Support Journal, asked where the drive to autonomy would find its energy in the coming years.

"Everyone you ask will have a different version of autonomy," offered Derek Novak, Chief Engineer at the American Bureau of Shipping (ABS). "While the basic degrees of autonomy have been laid out by the IMO, our perception is that flag states, owners, and OEMs all want to figure it out in practice. Flags will go forward through their domestic channels first. These projects will relate to simple routes going from A to B, but also work boats like fire-fighting vessels and tugs," he said.

—
Michael Carter
Acting Associate
Administrator
Environment and
Compliance
MARAD

Novak noted that ABS is taking part in an autonomous tug project in Singapore with ABB and Keppel. During the initial phase of the project, the vessel will complete a series of navigational tasks in a designated test area in the Port of Singapore, steered from an onshore control center. The second phase will see the vessel perform autonomous collision avoidance tasks while under remote supervision. The trials aim to validate the increased safety and efficiency of tug operations by utilizing digital solutions already available today.

“The focus is to be able to mirror a tug’s tasks and predict necessary actions,” Novak said. “First, we will look at augmented operations, then more automation, then autonomous. You have to walk before you can run.”

Ole-Jacob Irgens, Global Sales Manager, PG Propulsion Solutions at ABB Marine & Ports, agreed that focus will be on specialized tonnage first, not least with an eye to crew safety. "First responders like fire fighters are a good example, where the crew could be put in danger. In that light, navies are likely candidates too," he added.

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We believe that the transition will come in increments.

Ethan Wiseman, Assistant VP, Fleet Manager at NYC Ferry, NYCEDC, commented: "We are seeing opportunities appear on how to supplement the jobs done in the pilothouse, for example by calling attention to critical details when officers are being overwhelmed with information. The risk is that, over time, such tools can become a crutch if crews become dependent on continuous flows of knowledge."

Capt. James C. DeSimone, COO of Staten Island Ferry, commented: "Underwriters and lawyers will have issues with autonomy, and that will keep dependence on machines contained for now. The Captain has an authority that is not easy to remove. For this reason and more, we believe that the transition will come in increments."

—
Allan Krogsgaard
Director of Business Development
DNV GL

Seeking standards at sea

Krogsgaard pointed out that the maritime industry lags behind aviation in applying automation. "One might think that travelling on water was easier than flying, but automation on ships is far behind airliners."

Palemia Field, Global Marketing Communications Manager, Digital Solutions at ABB Marine & Ports, offered an explanation: "We have to be careful not to benchmark against aviation. The difference between aviation and maritime is that all airline manufacturers must adhere to the same standards. This is not the case with ships. Just look at the work that goes into designing each individual pilothouse."

Lack of universal standards for data management and the large number of third-party suppliers in shipping compared to aviation were also noted as factors contributing to the overall low level of standardization in the maritime industry.

—

First we need to know which problems we want to solve, then we can properly instrument a vessel in order to measure what we need.

When boring is better

Rune Braastad, SVP, Division Manager at ABB Marine & Ports US, stated that the business case for automation will likely not be found in crew cost savings. Instead, he believes that autonomy will prove its worth in enabling more efficient operations.

Field supported this argument: "The savings on crew are not significant yet. We might save on salaries by cutting crew, but how much of that would we lose on higher insurance premiums? Remotely monitored and controlled ships will require much more bandwidth and connectivity, and this costs money. The technology is good enough, and the regulatory framework is gradually becoming doable. But what are the overall benefits?"

Krogsgaard emphasized that regulatory requirements should not hinder developments allowed by rapidly emerging technologies. In order to narrow the gap between the possible and the permissible, Krogsgaard tells that DNV GL and their industry colleagues are trying to develop guidelines for automation that may allow broader utilization of available technology.

Regarding technology used to support onboard crew, the comment was made that the maritime industry seems often unsure of what to do with all the information they are collecting. "Big data is a big challenge. We are often not sure what to do with all the information we have access to," DeSimone commented.

"A lot of data collected may not actually be that important or relevant," Novak observed. "First we need to know which problems we want to solve, then we can properly instrument a vessel in order to measure what we need."

Field pointed out the importance of makers letting their machines do what they do best: "The greatest

—
Ethan Wiseman
Assistant VP
Fleet Manager
NYC Ferry
NYCEDC

need is to use data to assist in making decisions. A lot of accidents today are prevented by human intervention, but the goal is for autonomy to make life boring. Humans like mundane results, and machines are better at doing the dull jobs."

Ready to face the future?

The group generally agreed that even though machines will take over more tasks from humans, onboard crew will still need to know how things work, if perhaps to a lesser degree.

So how to prepare crews of the future for increasing autonomy onboard? Snyder posed the question to Bradley Golden, professor at Webb Institute: "Students are very interested in the subject of autonomy," Golden replied. "Right now, there are many post-grad subjects that focus on control systems, and we see a growing interest in applying autonomy to navigation."

Students at Webb are currently are using a trimaran craft to test autonomy, Golden said, following

—
Derek Novak
Chief Engineer
ABS

the stepwise approach currently in favor: “The main challenge is for it to stop before hitting fixed objects. When that is achieved, they will attempt for it to avoid moving objects,” he said. In order to meet future requirements, he emphasized that training institutions must maintain an open dialog with the shipping community: “What we really want to know is what the industry needs.”

But with autonomy continuously evolving, when will the industry be ready to say what it needs? Paul Benecki, Staff Writer for The Maritime Executive, asked how much better autonomous systems have to be before they can be implemented: “I wonder whether the industry really knows what good enough is?”

At this, sentiment around the table rallied behind the benchmark of accountability. Edward Schwarz, Vice President Sales, ABB Marine & Ports US, brought the focus firmly back on safety: “We would simply not consider implementing autonomy where it might introduce a liability.”

Maid of the Mist opts for electric future

Seeking a sustainable platform for their next generation of tourist ferries, Maid of the Mist found a natural solution in the all-electric option. President Christopher Glynn shares their reasons for going electric.

The awe-inspiring force of nature that draws millions of visitors to Niagara Falls in New York State each year will now power the boats carrying tourists to the foot of the falls. New Maid of the Mist vessels will deliver a silent and emission-free experience for passengers, driven by electricity generated from the Niagara River.

There is a great interest in sustainability today.

"We calculated some savings compared to fuel costs in the move to electric, but this was not the primary motivation," says Maid of the Mist CEO Christopher Glynn. "More significantly, there is a great interest in sustainability today, including low or no emissions. Once we decided to make the shift to all-electric, I was confident that our team had made the right call."

The latest generation Maid of the Mist vessels are welded aluminum catamarans with batteries powering twin electric propulsion motors capable of a total 400 kW output. "Our new boats are not bleeding edge, but leading edge," says Glynn. "The technologies are well known, but this is the first time they have been employed in this context in the U.S."


MAID OF THE MIST

Climbing the learning curve

The modern ferries represent the latest renewal of nearly 175 years of tradition. "Maid of the Mist has a truly great history," says Glynn, himself a second-generation CEO. "The company has always evolved with the times and the technologies."

— Christopher Glynn
CEO
Maid of the Mist

The first Maid of the Mist, a side-wheel steamboat, ferried passengers between Canada and the United States back in 1846. In 1848, with the construction of a suspension bridge between the two countries, the Maid of the Mist began as a tourist sightseeing service. The second Maid of the Mist, a single-stack paddle wheel steamboat, began taking passengers to the Horseshoe Falls in 1854. The first steel-hulled Maid of the Mist vessels were launched in 1955, also marking a shift to diesel power.

When research on the latest replacement boats began in 2018, the idea of electric propulsion quickly rose to the top of the list. "Niagara Falls is a great power producer. In fact, we are located on the site of a former power plant," says Glynn.

Once we decided to make the shift to all-electric, I was confident that our team had made the right call.

To familiarize himself with the available options, Glynn attended a conference on electric and hybrid marine propulsion technologies in Amsterdam in 2018. "Basically, I listened and learned. That conference opened my eyes to the attractiveness of electric propulsion."

Next up was clearing the idea with his insurers. "We had to show them that enough advances had been made in the field to justify the decision. The fact that we were able to win their confidence is a reflection of the state of the technology, but also of our team's ability to understand what was needed and when in the process."

Glynn refers to developments in electric ferries as a prime source of inspiration, most notably the Ampere ferry in Norway, in service since 2015. "We share basically the same charging cycle with the Ampere, so this was a good case for us to learn from."

Comprehensive cooperation

"We are located in the oldest state park in United States. The state is our landlord, but we receive no public money. We do get strong moral support from the State of New York though," Glynn points out. "It has been a symbiotic relationship, good for them, and good for us. This should be a bellwether project for New York in their push for improved sustainability. The community and the park will leverage any development that the new vessels represent, and Maid of the Mist will most likely gain from public engagement in sustainable operations."

Glynn observes that propulsion systems are progressing to support the trend toward zero emissions, noting that ABB has been a good partner in the search for the best solutions. "We have come to know them, and they have been sincere and open in their dialog with us."

Located in a climate with harsh winters, Maid of the Mist faces the challenge of what Glynn calls 'six-month years'. "We needed to renovate our facility during the summer months to accommodate the new vessel. All the ABB people have embraced that challenge and helped us to make it happen."

Renewal with respect

Not only the new Maid of the Mist propulsion systems, but also their appearance will be noticeably different. "Catamaran design is the way forward. Regulations for the number of passengers we want to carry no longer support monohull designs. The catamaran is simply more stable, and it presents a visual change to mark our shift to sustainable power."

With all the focus on modernization, the gravity of operating one of the oldest and most popular tourist attractions in the US is not lost on Christopher Glynn. "Our family has renewed the fleet several times since taking over Maid of the Mist in the 1970s," he notes. "With this latest move we would like to think that we are continuing the tradition of innovation to be carried forward by the next generations."

The community and the park will leverage any development that the new vessels represent, and Maid of the Mist will most likely gain from public engagement in sustainable operations.

For the immediate future, Glynn is confident in that Maid of the Mist has made the right choice with electric propulsion. "Now we are very excited to see how it performs. It will be quiet and clean, with an overall better passenger experience. I believe it will be very well received."

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The path to a carbon-free maritime industry
Investments and innovation

On January 14 2020, Peter Bryn, Technical Solutions Manager in ABB Marine & Ports North America, testified before the United States House of Representatives Subcommittee on Coast Guard and Maritime Transportation. The following is a synopsis of his testimony.

ABB is a market leader in power grids, advanced manufacturing technology, and electric transportation in the U.S. This includes electric vehicle charging infrastructure and marine and port electrification and automation solutions. With the marine industry in the early stages of a transformation to low and zero-emission technologies, the following points summarize ABB Marine & Ports' main arguments for an electrified, zero-emission fleet:

1. **Electric propulsion systems can help marine vessels get to zero emissions**
   Most alternative propulsion system arrangements are centered around an electrified propulsion system, including diesel or LNG electric hybrids, fully battery powered ships, and fuel cell powered ships. Electric propulsion not only cuts emissions but also improves safety and reliability, while reducing lifecycle costs. An electric-based powertrain may also be considered as futureproof, able to accommodate new power sources as they are developed. Whether power sources consist of fuel cells, batteries, ammonia-fueled generators, or a wave energy harvesting system, electric powertrains can integrate them. This is especially important for Jones Act vessels that will likely undergo power system retrofits over their long service lives, often spanning more than 50 years.

2. **Fitting the right solution to each vessel is critical**
   Vessel types are as varied as the missions they serve and the cargoes they carry. Ferries, inland towboats, harbor tugs, offshore workboats, and oceangoing vessels all have different operational characteristics that require different low or zero-emission technologies. Fortunately, a number of low and zero-emission technologies are either available today or under development, from diesel electric hybrids to fuel cells, full battery electric, and net-zero fuels. Accordingly, policies should focus on setting emissions targets for the marine industry, allowing the industry to assemble the best technology solutions for meeting emissions and operational goals, and provide support to the marine industry as they meet those targets.

3. **Lifecycle costs of electric powertrains are typically lower than for conventional diesel power**
   Vessels powered by electric propulsion systems and ship-wide direct current (DC) electrical system typically cost less to operate over the lifetime of the vessel due to higher

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Peter Bryn, Technical Solutions Manager, ABB Marine & Ports North America, testifies before the United States House of Representatives Subcommittee on Coast Guard and Maritime Transportation.

energy efficiency, lower maintenance and lower fuel costs. However, their upfront capital costs tend to be higher. This challenge is similar to that experienced by other recent energy technology breakthroughs, like wind and solar power and electric vehicles. However, thanks to a wide range of research, development, and deployment policies and incentives, those upfront costs have come down considerably and have reached or are approaching cost parity. The same will happen to zero-emission marine technologies.

4. **Low and zero-emission marine vessel technologies are in the early stages of adoption and need government and policy support**
   Today there are commercially available zero-emission marine technologies for some segments, like ferries. However, they tend to be more expensive upfront to purchase, which is a big deterrent to ship owners and operators, even though such solutions may be cheaper to operate. For other segments like offshore workboats and oceangoing vessels, cost-effective commercially available zero-emission solutions are still in the very early stages of development. To lower costs and reach a fully zero-emission vessel fleet, deployment of existing technology and development of new technology must be expedited. The industry would benefit from government investments in research, development, and deployment of zero-emission marine technologies.

Reducing marine emissions
We are in the very early stages of a transformation of the marine industry to low and zero-emission technologies. While ports have already begun their march toward electrification, which enables zero-emission operations, the marine sector is just getting started. ABB provides ship and port electrification and automation technologies and solutions. From replacing diesel powered cranes at ports with electric solutions powered by microgrids, to fully electrifying marine vessel propulsion systems, and everything in between, we believe the future of the maritime industry will be electric, digital, and connected. These technologies are used in ports across the U.S., from Charleston, South Carolina to Long Beach, California. The Coast Guard has also deployed one of ABB's advanced diesel-electric hybrid propulsion systems on the Great Lakes Icebreaker, the USCGC Mackinaw.

Global adoption of zero-emission technology

Globally, the maritime industry remains dominated by diesel-power, but a significant shift in energy sources is underway. The adoption of low to zero-emission ship technology is shown in Figure 1. While conventional power plants still dominate, a significant jump in both battery powered and liquified natural gas (LNG) ships is evident in Figure 2.

Alternative fuel uptake (percentage of ships)

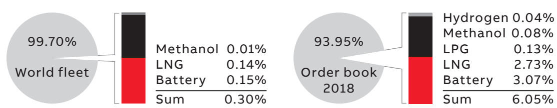

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Figure 1: Alternative fuel by ship count (DNV GL, 2018)

Source: DNV GL's Alternative Fuels Insight (AFI) portal, https://www.dnvgl.com/services/alternative-fuels-insight-128171

By vessel type, certain technologies are emerging because they complement the vessel's operational profile. For example, ferries are strong candidates for batteries because of their short-distance operation and predictable port calls, conducive to utilization of shore chargers. Conversely, containerships travel long distances and have extremely high power demands. Battery and fuel cell technologies require will require more research and development before they are able to meet the needs of oceangoing vessels cost-effectively, leading many operators to opt for LNG.

Electrified propulsion systems

Most alternative propulsion system arrangements are centered around an electrified propulsion system, including diesel or LNG electric hybrids, full battery, or fuel cells. Electric propulsion not only cuts emissions but also improve safety and reliability while reducing lifecycle costs. An electric-based powertrain is critical as it allows for easy integration of current and future power sources, important for Jones Act vessels that will likely undergo power system retrofits over their long service lives.

Fitting the right solution

Vessel designs vary significantly, each dictated by the vessel's application and purpose. The low and zero-emission technologies that will be selected for a particular project will be dictated by the needs and operational profile of the vessel. These technologies may include:

Low Emissions

- Diesel-Electric
- Diesel-Electric with Battery
- Diesel-Electric with Battery and Shore Charging
- Power Take In/Take Off (PTO/PTI)
- LNG/dual-fueled engines
- Biofuel (some)
- Fuel Cell with Fossil-Derived Fuel

Net Zero Emissions

- Full Battery-Electric Propulsion and Shore Charging
- Fuel Cell with Net-zero Fuel
- Biofuels (some)
- Ammonia

May 2019 status of uptake of alternative fuels by ships in operation and in order

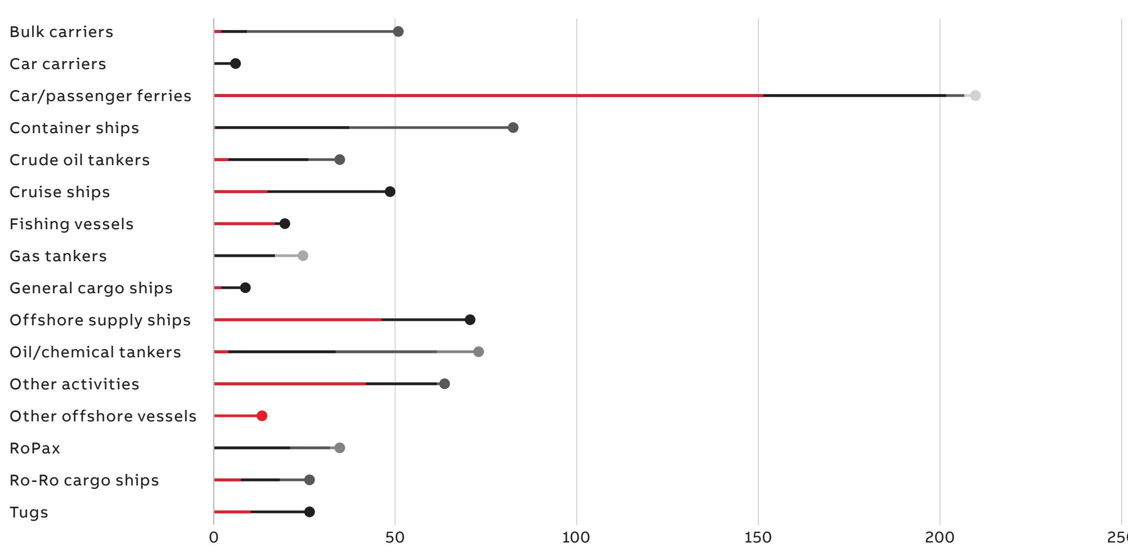

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Figure 2: Alternative fuel by ship type (DNV GL, 2018)
- Battery*
- LNG
- LNG ready
- Methanol
- LPG
- Hydrogen

* Includes fully electric vessels, and chargeable and non-chargeable hybrids

Source: AFI, DNV GL

It is critical that ship owners and operators identify the proper solution for their vessel, whether using conventional diesel engine arrangement or some combination of low or zero-emission technologies. For example, a harbor tug with significant idle time but using short bursts of full power during operation has a very different operational profile than a Very Large Crude Carrier (VLCC) tanker trading internationally on the spot market across oceans, often spending days at anchorage. Failing to consider a vessel's operational profile may lead to selection of a propulsion plant that is less efficient and cost effective than the diesel-mechanical baseline.

ABB works with many Jones Act vessel owners, operators, and designers to help them find the best solution for their operations. This ranges from ferries and fishing boats to harbor tugs and dredgers, passenger vessels, and river towboats.

Across segments, several recurring challenges persist: First, while the total lifecycle cost of ownership of a vessel powered by electric propulsion is lower than for a diesel-powered vessel, the upfront costs are often higher. Second, research, development, demonstration, and deployment investments are needed to bring down costs of these new systems and commercialize zero emissions solutions for more challenging applications like high speed catamarans and oceangoing cargo vessels.

U.S. newbuild market

In the private sector, newbuild construction in the U.S. is largely dominated by Short Distance Shipping (SDS) vessels, particularly tugs, towboats, and passenger vessels. By comparison, the number of Oceangoing Vessels (OGV) is small, as shown in Figure 3.

U.S. vessel deliveries by year

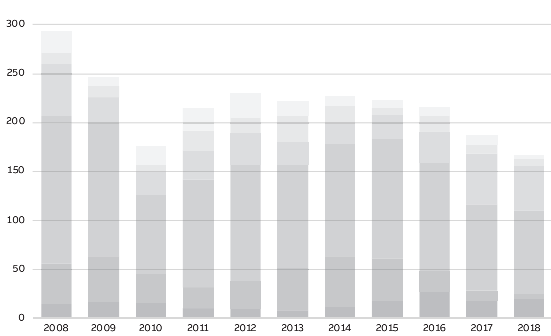

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Figure 3: Recent US newbuild construction (Colton, 2019)

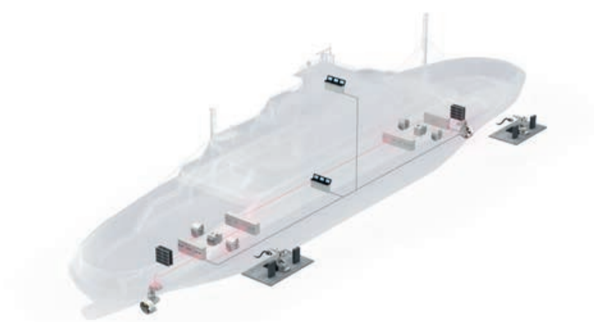
- SDS – Other
- SDS – Fishing
- SDS – Pax vessels
- SDS – Tugs and towboats
- OGV – Offshore service vessels
- OGV – Cargo, government

There are some exciting opportunities for Jones Act oceangoing vessels in the burgeoning offshore wind market, government fleet, offshore oil and gas activity, and larger cargo vessel markets. However, the bulk of this testimony will focus on the coastal and inland vessel markets where most US newbuild construction occurs.

Common U.S. vessel types and solutions

Road and passenger ferries

Ferries have become one of the pioneering vessel types for zero-emission battery deployment because they combine generally shorter routes with regular port visits. Shorter routes allow installation of battery packs that can fully power the vessels on their journeys, while the predictable routes and turnaround times enable efficient deployment of shoreside charging infrastructure.



Operational profile	Fixed route, limited distance, not overly weight sensitive, volume limited
Conventional solution	Diesel mechanical to propeller
Reduced emission solution	Diesel electric with battery with propulsion motor to propeller
Zero-emission solution	Battery-electric with propulsion motor to propeller
Common challenges	Charging infrastructure, utility demand charges

Not surprizingly, the ferry industry is among the first marine segments to adopt full battery-electric solutions. The two new Maid of the Mist ferries, with power systems supplied by ABB, are the first fully electric, battery-powered vessels to be built in the US. These Niagara Falls tour boats will be powered by a pair of battery packs with a total capacity of 316 kWh, split evenly between two catamaran hulls creating two independent power systems providing full redundancy.

The vessels will charge between each 20-minute round trip while passengers board and disembark. Shoreside charging will only take seven minutes, allowing the batteries to power electric propulsion motors capable of a total 400 kW (563 HP) output. This will all be controlled by ABB's integrated Power and Energy Management System (PEMS), which will optimize the energy use on board.

2.0 results – lifecycle cost calculation

	(A) Diesel mechanical (DM)	(B) Diesel electric (DE)	(C) DE w/battery for peak shave	(D) DE w/battery & shore charge	(E) Battery electric vessel	(F) Shaft generator vessel	
CAPEX	$0.66	$1.33	$1.46	$1.61	$1.50	$1.62	$M
AVG OPEX	$0.31	$0.26	$0.24	$0.20	$0.17	$0.24	$M/yr
ANALYSIS 1: Payback years							
Payback years	-	11	12	9	6	13	yrs
ANALYSIS 2: Internal rate of return							
Internal rate of return	-	8%	7%	11%	19%	6%	
ANALYSIS 3: Lifecycle total cost of ownership							
Lifecycle cost*	$4.5	$4.5	$4.5	$4.2	$3.7	$4.6	$M
Lifecycle savings	-	$0.0	$0.0	$0.3	$0.8	-$0.1	$M

*25 year life, 7% discount rate

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Figure 4: Example of actual project economics for ABB ferry project

3.4 CO_2 emissions summary

	(A) Diesel mechanical (DM)	(B) Diesel electric (DE)	(C) DE w/battery for peak shave	(D) DE w/battery & shore charge	(E) Battery electric vessel	(F) Shaft generator vessel	
Fuel and running hours							
Diesel fuel consumed	79,213	69,100	67,098	34,097	0	65,606	gallons/yr
Electricity consumed	0	0	0	497,636	1,039,034	0	kWhe/yr
Emissions totals (diesel emissions intensity per EPA; electric emissions intensity based on average for California)							
Diesel fuel CO_2 emissions	806,391	703,439	683,058	347,111	0	667,870	kg CO_2/yr
Electricity CO_2 emissions	0	0	0	107,261	223,954	0	kg CO_2/yr
Total emissions	806,391	703,439	683,058	454,372	223,954	667,870	kg CO_2/yr
Total reduction	-	**102,953**	**123,333**	**352,020**	**582,437**	**138,522**	kg CO_2/yr

Total emissions (kg CO_2/yr)

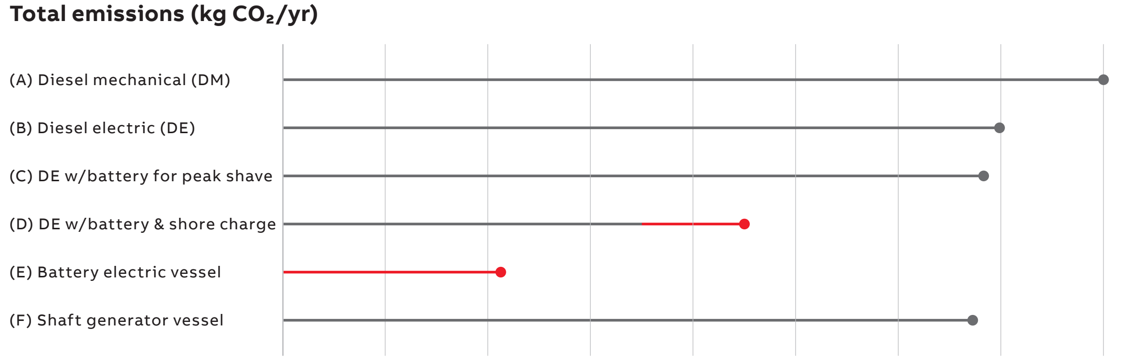

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Figure 5: Example of actual project emissions estimate for ABB ferry project
● CO_2 (electricity)
● CO_2 (diesel)

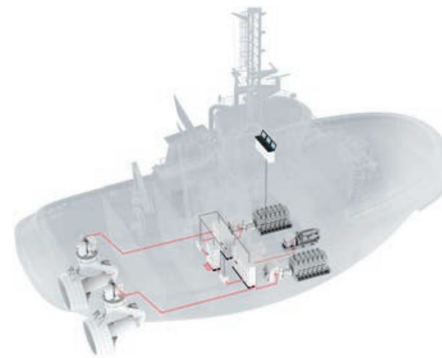
From small to large, most ferries and routes can be electrified. In 2018, two ForSea ferries, operating between Denmark and Sweden, became the world's largest battery powered ferries, following an ABB-led conversion.

Economics play a large part in the push toward electrification. While zero-emission boats tend to have higher capital costs, operational costs are much lower than diesel powered ships, making them more cost-effective over the lifetime of the vessel. Figure 4 is an example from a ferry project where the battery electric option (Case E) is more expensive up front, but because it costs less to operate, the ship owner or operator ends up saving USD 800,000 over the life the vessel. Just like with electric vehicles, increased deployments together with research and development can help lower the upfront capital cost of zero-emission options.

In addition to the cost savings of choosing a zero-emission solution, CO_2 emissions reductions are evident, as shown in Figure 5. A significant reduction of CO_2 is shown in Case E, which assumes an emissions profile in line with the energy generation mix of the power grid in California.

Harbor tugboats

Like ferries, harbor tugs operate on short routes and typically return to the same port every evening. However, unlike ferries, they have significant idling time and higher power demands. To reduce emissions, a diesel-electric system with a smaller diesel generator and a battery bank can satisfy onboard power requirements when stationary, while being ready to provide instantaneous maneuvering power.



Operational profile	~60% idle time, ~35% at <40% power, <5% at full power
Conventional solution	Diesel mechanical to propeller
Reduced emission solution	Diesel electric with peak shaving battery, possibly plug-in, propulsion motor to propeller
Zero-emission solution	Battery-electric or fuel cell-electric, propulsion motor to propeller
Common challenges	Space for battery room, sometimes unpredictable periods away from dock

Figure 6 is an example of a typical tugboat use-case where Cases C and D were recommended by ABB. Like the ferry example above, despite higher upfront capital costs, the lower operating costs of an electric propulsion system can save the ship

2.0 results – lifecycle cost calculation

	(A) Diesel mechanical (DM)	(B) Diesel electric (DE)	(C) DE w/battery for peak shave	(D) DE w/battery & shore charge	(E) Battery electric vessel	(F) Shaft generator vessel	
CAPEX	$2.20	$5.53	$6.68	$7.88	$10.16	$6.48	$M
AVG OPEX	$1.85	$1.58	$1.30	$0.82	$0.52	$1.36	$M/yr
ANALYSIS 1: Payback years							
Payback years	-	12	8	5	6	9	yrs
ANALYSIS 2: Internal rate of return							
Internal rate of return	-	7%	11%	20%	17%	11%	
ANALYSIS 3: Lifecycle total cost of ownership							
Lifecycle cost*	$25.3	$25.3	$23.8	$19.2	$18.6	$24.0	$M
Lifecycle savings	-	$0.0	$1.5	$6.1	$6.7	$1.3	$M

*25 year life, 7% discount rate

Figure 6: Example of actual project economics for ABB tugboat project

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owner operator over USD 6m over the life of the vessel. Programs that help increase deployments will enable price reductions that come with scale and experience. For example, a low-interest loan program to cover the difference in capital cost could boost adoption.

Inland towboats

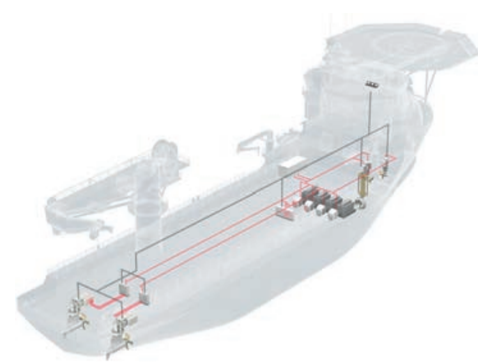
Inland towboats operate under a wide range of profiles. Factors like voyage length and consistency of docking schedule will support either battery-electric or fuel cell-electric solutions. Less ambitious emission reductions can be achieved using a diesel-electric hybrid system with a battery.

Operational profile	Unit tows: varying length voyages Shuttle boat: short distance transits, long idle time Fleeting boat: stays local to fleet moving barges in and out Linehaul boat: regular long-distance hauls
Conventional solution	Diesel mechanical to propeller
Reduced emission solution	Unit tows, shuttle boat: Diesel electric with battery Fleeting boat: Battery-electric Linehaul boat: PTO/PTI
Zero emissions solution	Unit tows, shuttle boat, linehaul boat: Fuel cell-electric Fleeting boat: Battery-electric
Common challenges	Highly capex-focused market, cautious about new technology

ABB is proud to be providing a complete fuel cell-electric power system for what will become one of the world's first fuel cell powered towboats, which will be operated by Compagnie Fluviale de Transport (CFT) of France.

Offshore workboats

Offshore workboats present yet another operational profile. Many have long dwell-times when servicing offshore assets like wind farms or oil and gas rigs, while also needing onboard power for ancillary service-related systems. A first step toward reducing emissions for these workboats is to add batteries to a diesel-electric system. The batteries can be used to optimize diesel performance by assuming highly transient loads arising from the podded thrusters as they start and stop while in dynamic positioning mode. The diesel may shut off completely, or if running, can operate at an optimal, steady level and avoid constantly ramping up and down. A movement to zero emissions will likely entail a fuel cell-electric propulsion system with battery.

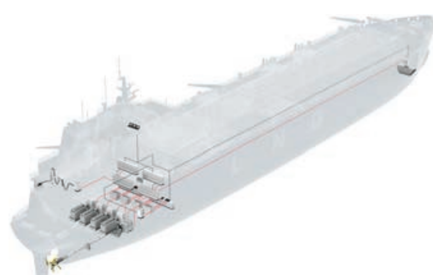


Operational profile	Varied, but often have high dwell times and significant non-propulsive loads
Conventional solution	Varies, but often diesel-electric with podded propulsors
Reduced emission solution	Diesel-electric with battery storage for optimized operation
Zero emissions solution	Fuel cell-electric with battery storage

ABB is proud to have powered the NKT Victoria, which features ABB's Onboard DC Grid™, enabling a remarkable 60 percent CO_2 reduction versus a comparable vessel. This was achieved due to both greater efficiency in the propulsion system, and operational changes enabled by the electrified system.

Oceangoing cargo vessels

Oceangoing cargo vessels often have predictable operational characteristics, but their long distance routes, coupled with very short port stays, make full battery-electric propulsion systems challenging. The first step toward reducing emissions is to use an alternative fuel like LNG or biofuel, potentially electrified with battery storage. A move toward zero emissions would likely incorporate a fuel cell-electric propulsion system, which ABB is developing on a larger scale (1-3MW) for just this purpose.



	At sea	In port
Operational profile	Most spend long periods of time at sea with limited port turnaround time	
Conventional solution	Slow speed diesel to propeller	Operate diesel-powered generators and steam boiler
Reduced emission solution	Alternative fueled (e.g. LNG, dual fuel), possibly with battery	Cold ironing (vessel plugs into local shore power) or battery
Zero-emission solution	Fuel cell-electric with propulsion motor to propeller, or engine with net-zero fuel (e.g. ammonia, biofuel) direct to propeller	

While in port, achieving zero emissions is possible for some vessels today by connecting to a shoreside power source, often called "shore power," "ship to shore," or "cold ironing". ABB has provided a number of cold ironing installations across the globe, providing both the onboard and shoreside equipment. There are challenges to cold ironing, as most older vessels are not outfitted to accept shore power and not all ports are currently equipped to support it. Also, cold ironing can be of limited value if there are substantial non-electric loads (e.g. crude oil tanker steam-powered cargo pumps) or if in-port power demands are not overly significant (e.g. a bulker with only hotel loads).

Summary and recommendations

The marine industry is just beginning its move toward zero emissions, with commercially ready cost effective solutions available today to meet the needs of many vessel segments. Yet certain segments such as oceangoing vessels will require significant additional technology research and development in order to reach the zero-emission target. One common factor across all segments, which is also true across many new technologies, is that with scale and experience, costs trend downward. This has been the case with solar and wind power, and also electric vehicles. The same will hold true for marine vessels.

There are a number of actions that the Federal Government and this Committee can take to increase deployment of existing zero-emission technologies, invest in the zero-emissions technologies of the future, and grow US leadership in the marine sector for decades to come:

1. **Green the Federal Fleet**
   The US government is a globally leading shipowner, and as such it can become a pacesetter in deploying cost-effective, advanced technologies. The non-defense US owned fleet includes Coast Guard, MARAD, and National Park Service vessels.

   ABB encourages the Committee to set an ambitious, long-term national plan to achieve zero emissions for all vessels under its ownership. Doing so would have a meaningful impact on vessel emissions and establish the private US maritime industry as a global technology leader. This would also help the US do its part toward meeting the IMO Sustainability Goals. ABB is prepared to support the Committee in developing such a strategy to seek realistic, cost-effective solutions.

2. **Limit Tier 4 Engine waivers to where true hardships exist**
   Following a thorough rulemaking process and cost justification, EPA requirements for reduced emission engines have arrived. Engine manufacturers have provided proven, cost-effective engine solutions to meet these requirements. While the EPA is not under the jurisdiction of this Committee, waivers for vessels under this Committee's jurisdiction should be issued judiciously and only after thorough demonstration of hardship to meet the requirement.

3. **Support financing mechanisms and direct funding for the private sector, zero-emission vessels, projects, and equipment providers**
   Zero-emission vessels often have higher up front capital costs, but lower operating costs and therefore lower total cost of ownership than conventional diesel systems. Government investment in research and development can help lower those costs. As such, we recommend supporting and expanding programs like the Maritime Education and Technical Assistance (META) Program. We also suggest exploring establishing a low-interest loan program to cover the incremental capital cost of choosing a zero-emission technology.

4. **USCG Marine Safety Center**
   The Coast Guard's Marine Safety Center (MSC) is faced with the challenge of ensuring the safety of vessels, regardless of propulsion technology. As lithium ion batteries, fuel cells, hydrogen, and other new technologies become commercially available, the MSC is tasked with updating the CFR's to address these new technologies. This will require time and resources. ABB is prepared to support MSC in this role and asks the Committee to do the same.

5. **Invest in R&D**
   While there are commercially available zero-emission solutions available today for some marine segments, others still require significant research and development, particularly in the area of fuel cells, advanced battery chemistries, and advanced net-zero fuels. Through the US Coast Guard's Research Development Test and Evaluation Program, the Department of Energy, and MARAD's META Program, the Committee could encourage development of a zero-emission ship research and development program.

6. **Help solve shore charging**
   As vessels like ferries electrify, electric utilities are faced with high power loads during recharge. This can often trigger demand charges which can significantly challenge the otherwise favorable economics of moving to electric. Solutions like shoreside energy storage systems are available to mitigate this cost, though they can add cost and complexity to the project. ABB applauds MARAD's work with the DOE to seek a national strategy to address this challenge, and asks Congress to support this initiative. The Committee could also direct MARAD to invest in shoreside power through funding mechanisms like the Port Infrastructure Development Grants.

7. **Training**
   Support Maritime Academies and ensure labs and curriculum include the latest technology. While alternating current (AC) electrical systems remains a common standard on vessels, ships powered by electric propulsion will be built using direct current (DC) architecture. Training curriculum should be updated to address these changes to how ships are powered.

ABB's commitment to reducing emissions

ABB has set as its goal to reduce its GHG emissions by 40 percent by 2020 from a 2013 baseline. ABB supports the Paris Agreement, which came into force in November 2016, and considers it the linchpin of efforts to limit global warming and avert the potential devastating consequences of climate change. ABB actively contributes to climate goals by encouraging the early and rapid adoption of clean technologies and by helping its customers improve energy efficiency and productivity while extending the lifecycles of their equipment and reducing waste.

Meeting the goals of the Paris Agreement will require significant investment in new and upgraded technologies, which will only be forthcoming with solid, reliable, and predictable policymaking. With around 9,000 technologists and investments of around $23 billion in innovation scheduled to take place between the signing of the Paris Agreement and 2030, ABB therefore urges policymakers to adopt sound climate policies to encourage innovation and create secure investment conditions.

ABB believes that investments in developing and deploying technologies that reduce climate impacts, while incrementally higher at first, lead to significant intermediate and long-term cost savings. Such technologies are core to ABB, as nearly 60 percent of ABB's global revenues are derived from technologies that directly address the causes of climate change through energy efficiency, renewables integration, and resource conservation. The marine sector also holds a similar promise of reducing emissions and overall costs.

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06
Technical insight

Artificial Intelligence
Machines learning from ABB experts to increase vessel efficiencies

As a frontrunner in electric, digital and connected solutions for shipping, ABB's latest fleet support and troubleshooting advance sees engineers 'training' machine-learning algorithms to deliver faster, more reliable remote services to customers.

MORTEN STAKKELAND
Data Scientist
ABB Marine & Ports

With eight ABB Ability™ Collaborative Operations Centers, ABB Marine & Ports delivers world-class support to customers worldwide. Now, its artificial intelligence (AI) training is combining data and machine learning with skills that only experienced engineers can pass on.

From locations in Europe, Asia and the Americas, ABB experts monitor shipboard systems, coordinate equipment diagnostics and offer maintenance services around the clock. In addition to providing a single point of contact through '24/7 care' approach, ABB's international centers share data so that staff can access the same information – and provide the same level of support – regardless of their location. Moreover, engineers can retrieve real-time data to help with resolving onboard issues or identifying anomalies before they become faults.

Artificial intelligence at sea

There are significant benefits in using AI in marine diagnostics and maintenance. The technology optimizes condition monitoring and, as a consequence, reduces the burden on crew members and engineers. The resulting increase in system reliability – and therefore also vessel performance – also improves safety.

It is clear, then, why shipping is ready to adopt AI on a larger scale – and its progress in the industry is being driven by several key factors.

For instance, machine learning techniques have advanced considerably in recent years, and software allowing these novel methods to be applied to industrial datasets is now more widely available. Just as significant are the wider availability of historical data and the presence of a digital infrastructure that allows information to be collected from vessels and stored in the cloud at a relatively low cost.

ABB is playing a key part in this development. Its 'Electric. Digital. Connected.' strategy encompasses every element in the digital ecosystem, facilitating the collection of data from connected machines and devices onboard ship as well as its secure storage in the cloud.

Learning from the past

Using past data to prepare algorithms for a specific purpose is fundamental to modern machine learning methods. An example of this practice in the maritime sector is predictive maintenance, in which past maintenance data combined with operational and failure data is used to develop a

condition-based approach able to predict malfunctions ahead of time.

Yet while historical data is undoubtedly crucial to machine learning, human input is equally important. Engineers – who for the past decade have been using the data to provide services like diagnostics, fault detection and troubleshooting – possess insight into customer equipment and systems that cannot be gleaned from data alone.

Against this background, ABB is developing interfaces to enable engineers to ‘train’ machine-learning algorithms. Enhanced by the unique insight of experienced professionals, the resultant AI systems will provide faster, more reliable service to customers throughout the sector.

Labelling data for supervised machine learning
Support engineers spend much of their time assisting customers whose operations have been disrupted by system or component failure. In such cases, the engineer assigned to the task will often manually download and inspect measurements and data from the relevant systems or subsystems to pinpoint the root cause and propose an appropriate solution.

As part of this process, he or she classifies the incident or fault. The dataset concerning a fault may consist of categorical data in the form of alarm lists, measurements from shipboard sensors and text-based information in the form of service reports or communication between the support team and crew.

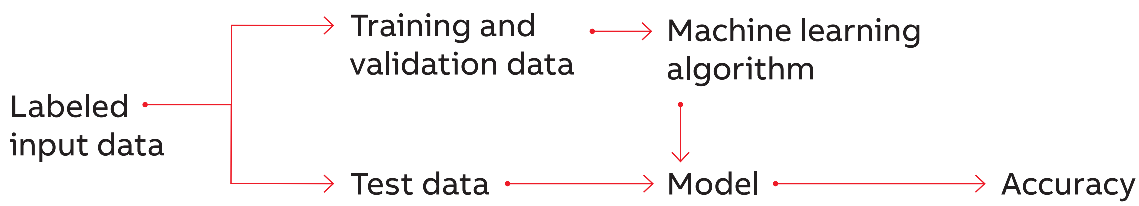

Figure 1: Process flow for supervised machine learning

Unlike unsupervised machine learning, in which little or nothing is known about the data, supervised machine learning relies on the data being clearly and accurately labelled. Figure 1 provides an overview of the process.

The labelled input data is frequently divided into training/ validation datasets and test datasets, which are used to prepare and verify the machine-learning algorithm. The algorithm selected depends on the application and the available dataset.

In the case of fault diagnostics in complex marine systems, a classification algorithm is employed. The underlying engine used to train the classifier varies depending on the dataset, but the training and testing process, as well as the deployment of the trained model into a production system, can all be integrated into the ABB Ability™ ecosystem.

Interaction with algorithms
Unsupervised algorithms cannot learn structure from labelled data, and instead have to identify that structure independently.

In cooperation with researchers from the University of Oslo, Norway, and as part of the BigInsight research project where ABB is a funding and contributing partner, ABB has developed an unsupervised system that takes output from marine systems and finds structure or clusters in the unlabeled dataset. The algorithm is based on advanced Bayesian statistical methods, accounting for the fact that datasets collected from marine applications do not constitute 'big data' on the scale of other industries such as the consumer applications market.

Each of the structures corresponds to a mode of operation of the equipment, including fault or failure modes. However, for these results to be useful, domain knowledge is needed to accurately recognize and name the various clusters or operational modes. An overview of the methodology is shown in Figure 2.

The developed model allows engineers to manually edit the cluster. For example, for a given fault class, an engineer may decide that a certain alarm or message delivered by the system is irrelevant and should not be considered as an indication by the algorithm.

The methodology will be applied to automated diagnostics and fault detection for complex marine systems. It will be integrated into the digital service offering and support onsite engineers in their maintenance work.

Combined power of human and machine
ABB is augmenting its support and troubleshooting services not by replacing human staff with AI, but by developing systems that combine the benefits of data and machine learning with skills and knowledge that only experienced engineers can offer. The more input the experts provide, the more intelligent the systems will become. This will ultimately improve the level of service provided to the customer, increase vessel efficiency, and make maintenance work easier and safer for the engineer.

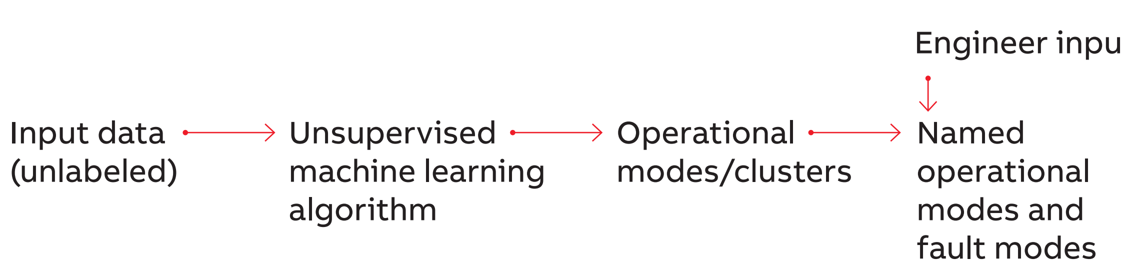

Figure 2: Process flow for unsupervised machine learning


ABB
Global Technical Support
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ABB Collaborative Operations
The key to efficiency, security and profitability

In today's complex, hyper-connected and increasingly globalized world, engineers, operations managers, and successful business leaders need accurate, real-time access to operational data to support better decision making.

ANTTO SHEMEIKKA
VP Digital Services
ABB Marine & Ports

Digitalization that enables optimization, streamlining, and automation is becoming increasingly important in innovating data-driven solutions and improving business results.

While access to data has always been important, the volume and penetration of data has increased exponentially in recent years. Data is now available on physical assets like vessels and factories, as well as within industry domains and regulatory frameworks. Horisontal integration in the information ecosystem empowers every role in the organization to achieve individual and collective objectives. Vertical integration across siloed business systems offers insight unimaginable only a few years ago.

A system of records that effectively leverages data, regardless of its source, is a key differentiator for organizations competing in a global economy, improving operations and optimizing costs, quality and productivity.

With improved access to steadily more data comes increased risk. Equally important to establishing a plan for acquiring and handling data is defining an in-depth cybersecurity strategy. Data privacy, trust and compliance are acknowledged as essential to any business transformation strategy.

Despite this, many companies lack a comprehensive approach to cybersecurity, leaving their most valuable assets vulnerable to attack. Compounding the problem is the lack of clarity between IT and OT leaders responsible for cybersecurity.

While there are significant differences between business and operational systems, alert operations leaders can apply many IT lessons to their OT systems. A successful cybersecurity approach employs multiple layers of protection across the computers, networks, programs and data that they have been assigned with safekeeping. In an organization, the people, processes, and technology must all complement one another to create an effective defense from cyber attacks.

There are many ways to start leveriging data for business benefits:
1. Optimize the collaboration between onshore technical teams and onboard technical staff by shared data.
2. Introduce Operational Centers to facilitate more efficient use of advanced applications, including structuring the work environment to support data-driven decisions.
3. In maritime operations, raise fleet status awareness through use of customized dashboards.
4. Utilize the latest human factor research to increase operator efficiency through effective use of hardware and design of operation centers to facilitate 24/7 work environments.

ABB Ability™ Collaborative Operations Centers set a new standard for 247 remote vessel support

Collaborative Operations connect people onboard the vessel, at headquarters, in the harbor, and at ABB operational support centers on shore by giving them the information to make businesses more transparent, agile and profitable.

In the marine service environment, digitalization through collaborative operations has been proven to reduce the need for engineers to perform on-board service by over 30 percent, in addition to reducing unnecessary service visits by more than 70 percent. Intelligent integration across engineering, infrastructure, devices, applications and services provides new insights from company data and empowers faster, and more astute decision making.

The true value of any infrastructure lies in the business benefits the data can generate. ABB has proven that collaborative operations and improved use of data analytics leads to reduced costs, optimized schedules and minimized risk through properly integrated digitalization.

Digital transformation through implementation of collaborative operations reaches across the entire organization and impacts all aspects of business. It requires cultural change management from beginning to end, and ranges from collaborative design and operations centers to management of industrial assets across the globe. Today, the digital transformation is not optional – it is an absolute prerequisite. Technological developments have now outpaced business processes, putting pressure on companies to constantly re-think their operations in order meet constantly evolving goals for to day-to-day performance.

ABB Collaborative Operations combines the platform, people, and cyber security measures necessary to bring ABB expertise directly to the customer, wherever they may be, providing powerful digital solutions that take advantage of today's operation and information technologies to help them increase productivity, optimize operations and ensure security.

Summary
ABB Collaborative Operations connects ABB with facilities, vessels, fleet managers, operators, giving them the right information to make their businesses more profitable.

Intelligent integration across engineering, management, infrastructure, applications and services ensures new insights to empower faster, more astute decision making.

ABB can improve the use of data analytics to cut costs, optimize schedules, and minimize risk through properly integrated digitalization.

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Sources:
1. ABB-MICROSOFT JOINT GUIDE Getting started with industrial digital transformation
2. ABB publications

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ABB Ability™ Collaborative Operations Center Manager USA, Luis Miguel Moratalla (front left) with colleagues working on a case

Machine learning
Believe it or not?

Combining the right data science with scalable IT solutions brings benefits to traditional marine engineering.

JAROSLAW NOWAK
Equipment Analytics
Global Product Specialists
ABB Marine & Ports

Machine learning techniques have advanced considerably in recent years. The software that allows these novel methods to be applied to industrial datasets is now widely available. The wider availability of historical data is equally as significant, strengthened by the presence of a digital infrastructure allowing information to be collected from operating vessels and stored in the cloud at relatively low cost.

In this arena of opportunity, digital leaders, technology managers, software developers and researchers working in marine industry often struggle to make the right choices in answer to such questions as:

- Is the cloud technology offered by an IT company going to perform according to my technical and budgetary expectations?
- Will machine learning methods used in medical research really help me solve my engineering problems?
- Can I trust my domain knowledge and my intuition, or should I follow up the advice and prognostics generated by a 'black box' algorithm?

ABB is a proven provider of state-of-the-art engineering solutions for the marine market. As such we deal with these questions on a daily basis. And as a company dedicated to incorporating modern technology trends into our domain, we are not afraid to think outside the box. Testing machine learning methods used in biostatistics to detect faults in our equipment is one example. Still, we want to proceed with a maximum understanding of the science behind the solution and guide our progress by using our knowledge as domain experts. In an effort to learn more about machine learning, ABB Marine & Ports Digital Service R&D team members have been educating themselves in data science methodologies, applying these to a few select technical cases, and deploying them with the support and use of different IT cloud platforms, in cooperation with internal and external IT teams.

The journey has begun, and it is already showing promise. Machine learning has become a strategic element in ABB Marine & Ports Digital Services, and we would like to share the lessons learned so far, in an attempt to stimulate discussions with our customers on this topic.

The technical cases presented here relate to data-driven modelling for the purpose of diagnostics and fault detection in marine equipment. In the specific context of problems presented, we analyze the modeling techniques to be tested. Discussion is then followed up with practical study of how developed models and scoring algorithms can be distributed and shared across multiple IT ecosystems to allow the data processing pipeline to be adjusted to fit the needs of each individual project and customer request.

What is data science?

The answer to this question probably depends on who you ask. A quick online search might reveal the

humorous attempt at an explanation shown in Figure 1. On a more serious note, if one asks statisticians or computer scientists about the difference between statistics and machine learning, stronger and more polarized opinions may be offered:

- “Machine learning is essentially a form of applied statistics”
- “Machine learning is glorified statistics”
- “Machine learning is statistics scaled up to big data”
- “The short answer is that there is no difference”

Or even more provocative:

- “Machine learning is for Computer Science majors who couldn’t pass a Statistics course”
- “Machine learning is Statistics minus any checking of models and assumptions”
- “I don’t know what Machine Learning will look like in ten years, but whatever it is I’m sure statisticians will be whining that they did it earlier and better”

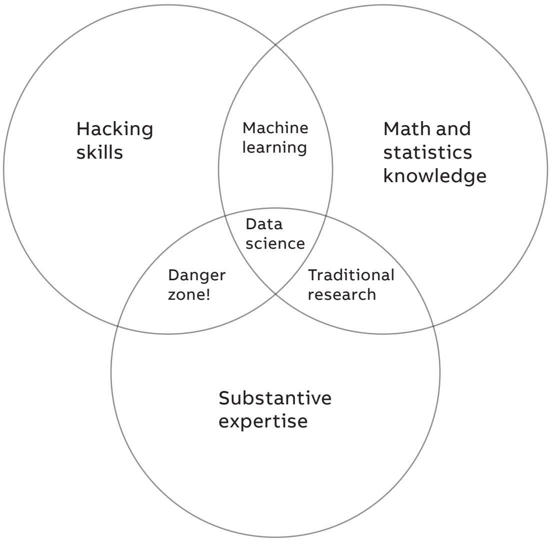

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Figure 1

Again, following the article listed under references: “The difference is about different goals and strategies.” It seems statisticians, when developing their models, are mostly interested in delivering a precise mathematical and statistical framework. Predictions from the model are not of primary importance, rather “the analysis is a final product.”

At the same time for machine learning practitioners, “the predominant task is predictive modelling. The proof of the model is a test set.” Due to fewer restrictions on proving the strict mathematical foundations of a model, machine learning users are free to choose from a larger set of models. In the case of so-called ‘black box’ techniques such as neural networks or even random forests and boosted decision trees, knowing the mathematical principles behind the algorithms does not necessarily make clear to which problems they should be applied. We may be very satisfied with the results of solving one problem, and yet disappointed and confused to see poor performance in a similar case with different data sets.

So where do industrial and marine engineers stand in this debate? Perhaps we are fortunate to represent disciplines based strongly on the laws of physics, thus offering us access to analytical models. We may have to simplify equations describing for instance power flow within the marine propulsion chain, but we still understand main principles and relations between most critical measurements. In that sense we are privileged compared to those who apply themselves to the study of biostatistics, medicine, or geology, to name a few. There, in the absence of understanding the complex mechanistics of processes, applying statistical or machine learning is the only way to indicate causality. The point is that engineers may enrich existing machine learning methods with prior knowledge about the expected mechanisms behind modelled data. The knowledge can be introduced with proper labelling of data and cases such as those described in the referenced article. Knowledge can also be applied using well-known and proven mathematical techniques originating from other disciplines such as process identification and theory of control.

Estimating pressure drop rate in medium voltage drive cooling systems

The first case to be discussed applies the absolute basics of machine learning. It is about forecasting the point in time when the pressure of internal cooling water in a medium voltage frequency converter (or drive) will hit its warning limit. The medium voltage frequency converter delivered by ABB is one of the critical components of an electric propulsion system. In that sense, developing analytics and predictions about the performance of the drive adds additional value for the customer. The frequency converter will function as expected if it is properly cooled. The closed water cooling system is characterized by a slow but constant drop in pressure of the coolant due to natural evaporation and normal leakage through pump seals. As a consequence, the cooling circuit must be regularly topped up with water. The maintenance work of adding the coolant must be performed while the frequency converter, and consequently the entire propulsion chain, is shut down. Therefore, this operation is typically planned well in advance, and knowing the expected timing of warning limits optimizes the planning process.

The machine learning model operating behind the scenes is the simplest, univariate linear regression of the pressure signal itself. It does not model the influence of temperature, nor it does it tell whether the pressure drop is as expected, or is accelerated and thus abnormal. Rather, within the dynamically adjusted time horison, it captures the linear fit of the pressure drop and calculates the time when it will intercept the warning limit (see Figure 2). As many gurus of statistics would say: “If the simple model works for its purpose – do not try to complicate it.”

This simple model has been implemented as a result of cooperation between ABB and the startup company Dutch Analytics, in an Artificial Intelligence accelerator program run by ABB in 2019. Dutch Analytics has also deployed this model in their highly scalable cloud platform Xenia, and integrated it with the main data and presentation pipeline hosted by ABB. Details on various scenarios of IT deployment of machine learning models are discussed later in this article.

Analysis of medium voltage bus bar temperature

The second case is an example of time series data types. Here, the number of covariates used in modelling is much larger, consisting of approximately 1000 various signals per vessel. Recorded data represent the relative temperatures of the medium voltage bus bars detected by infrared sensors inside medium voltage switchboard cabinets. In addition to temperature, the current circuit breaker output from the cabinet is also measured.

The goal is to build a model that helps detect abnormal temperatures in the system. The challenge is that this is a purely unsupervised case where no failure has yet been observed in the system. The approach is to construct a model derived from a training data set using a new system with

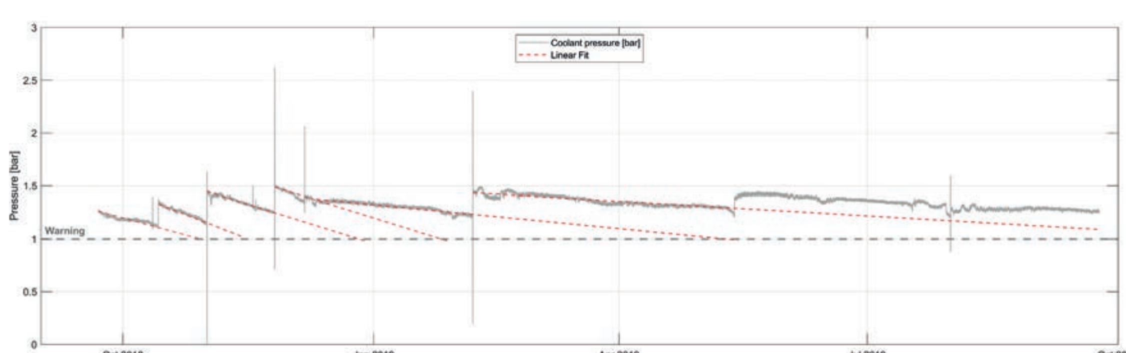

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Figure 2

no defects. Next, we use this model to track the difference over time between the prediction from the model and the actual measurements (so called residuum). As a result, once the residuum processing part of the algorithm indicates abnormality, an early warning is sent to the human expert (in this case an ABB service engineer).

In this case, applying multivariate linear regression or even generalized additive models does not seem to provide immediate or positive results. This is mainly because time series data are are represented differently than typical data sets successfully modelled and predicted by major statistical inference methods. For instance, in disciplines such as biostatistics or genomics, each data sample is to be distinctly treated by the model's learning process. By contrast, time series data originating from industry includes the dynamics of the process, e.g. with transients between different states, and those transients should also be included in the model (see Figure 3).

The solution is use of methods for dynamic system identification that are well known from process identification and process control studies. Here however, strong analytical knowledge of the process generating the data is required. Descriptions using state space models, Laplace transforms or direct differential equations is quite cumbersome, often even impossible, but with some simplification controlled by domain, a marine engineer can combine deterministic and stochastic descriptions into something resembling a Kalman filter framework.

We strongly believe that there is huge potential to outperform typical statistical and machine learning methods using this approach.

For this second case, the ABB Marine & Ports Digital Service R&D team and a research group of statistics and data scientists at the University of Oslo are conducting research to combine statistical methods with those specific to process industry, in order to model cases as described in previous sections of this paper. We believe this cooperation will produce applicable decision support systems that will help to optimize maintenance procedures for onboard marine equipment.

Model deployment tests in the cloud

Once the model is ready to consume and process newly measured data, enabling it to produce predictions (scoring results), the IT architecture is introduced and a decision reached on where the model is to be deployed. Again, there are many different scenarios, but in the interest of simplicity, we assume that the model can be running either:

- At the edge, e.g. directly on site, where the data collection is taking place. As depicted in Figures 4 and 5, our model is to be part of an onboard data collection and remote diagnostic system (RDS)
- And/or in the cloud, where we can leverage the latest IT technologies to handle big data, run scalable solutions and exchange data and models across different platforms owned by various stakeholders (system providers, ship operators, class societies)

Our focus in this case is on the cloud deployment architecture. As a test case, we selected time prediction of water top-up in the medium voltage drive's cooling system. The team included data scientists from Dutch Analytics and ABB and architects from the ABB Ability™ Analytics platform, and was moderated by the ABB Marine & Ports Digital Service R&D team. The goal was

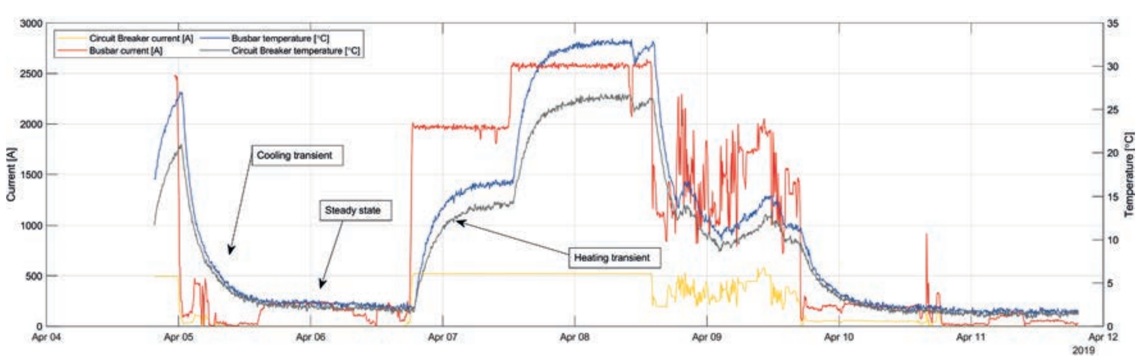

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Figure 3

to understand technical capabilities, required effort and cost of IT deployment and operation needed to run the same model within different cloud architecture stacks. Technologies selected include Xenia, a product of Dutch Analytics, utilizing Google cloud solutions and the ABB Ability™ Analytics platform based on Microsoft Azure cloud technology.

The model itself is implemented in Python and consists of two modules. First, the Data Cleansing element organizes raw data sets into a common time grid and manages measurement gaps. Following that is a Model Prediction module that first estimates coefficients of the linear model with use of specific time horison, and then predicts the date when the warning limit is expected to be reached.

The overall data and analytics pipeline is presented in Figure 4 and Figure 5, where Figure 4 presents the solution deployed in the Xenia platform (case A) and Figure 5 in the ABB Ability™ Analytics framework (case B).

Both have in common the way in which data are collected onboard and securely transferred in batch modes as compressed files into cold storage inside the ABB network. Next, data is extracted and transformed to plain text format that can either be pushed via a REST interface to XENIA blob storage, or within the same ABB ecosystem to Azure blob storage. The heart of data processing and analytics in scenarios A and B is deployed into two different cloud eco-systems, yet they share common technologies such as Spark Databricks, relational databases and web services. Eventually, scoring results will be presented in the fleet operating center dashboard.

Xenia from Dutch Analytics is built on a modern micro-service based architecture, making it efficient at scaling and distributing computation loads using Kubernetes as an auto-scaling framework. The goal of Xenia is to provide a powerful abstraction layer for robust execution of data science code, ensuring efficient resource management without requiring that the user be a DevOps expert.

ABB Ability™ is the company's unified, cross-industry, digital offering – extending from device to edge to cloud – with devices, systems, solutions, services and a platform which enables customers increase productivity and lower costs. ABB Ability™ was launched in 2017 and already offers more than 210 solutions.

Using principally the same Python code that implements both Data Cleansing and Model Prediction modules, the multidisciplinary team from Dutch Analytics and ABB could functionally prototype the same pipeline in two different IT platforms. The tasks of making code and interface adaptation, meetings and discussions, and final deployment tests of the prototype took around 80 hours total for the entire team.

The result of the above exercise is more prototype than final product, but it gives an idea of how little effort is required, and in principle how easy it is to run similar proof-of-concept integration tests. Many lessons have been learned, covering aspects from pure data analytics to collaboration effectiveness, concluding with cloud IT technology specifics.

Learnings
For Jaroslaw Nowak, a member of ABB Marine & Ports Digital Service R&D team, and whose role it is

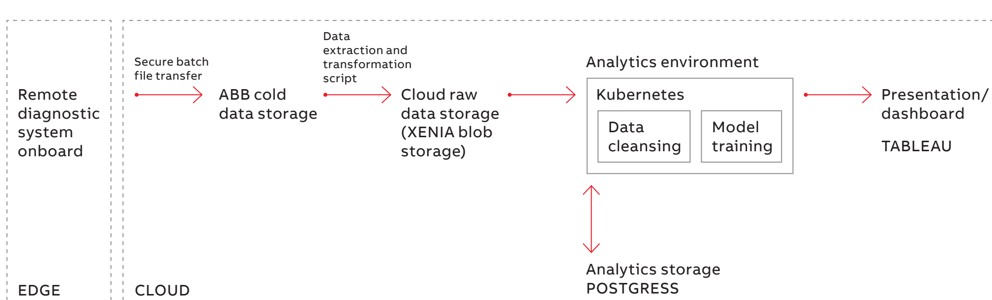

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Figure 4: Duch Analytics Xenia platform

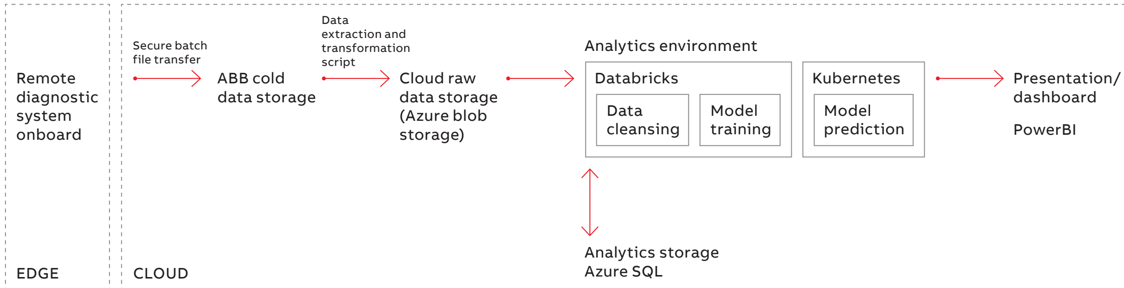

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Figure 5: ABB Ability™ Analytics platform

to develop early prototypes that may be turned into products, the learning can be summarized as follows:

- With a team of experts in their domains focusing on delivering quick and tangible results, it is surprisingly easy to build various cloud data analytics pipelines.
- A key factor for realizing the above statement is for implementation of each pipeline discussed in the text, even though they may be deployed within IT frameworks offered by different suppliers, to be based on the same or very similar technologies, such as Spark Databricks, Kubernetes, relational databases and web services.
- From a business perspective, running such an exercise should be an initial, mandatory step in each analytics-in-the-cloud-integration type of project. This is when parties such as ABB, with their end-to-end solutions, customers with a desire to know more about their assets, and third-party data scientist or platform providers already part of an existing IT eco-system, are asked to collaborate and build an integrated solution.
- Modelling and diagnostics, let alone applying known machine learning methods to sensor data as they come, may not provide answers to questions such as whether equipment is in a faulty state. It seems that organizing and properly labelling data, combining multiple sources of information (sensor data, maintenance log data), and numerous discussions with marine domain experts to define algorithm goals, are all activities fundamental to proper selection and synthesis of machine learning algorithms. Without these, the quality of predictions given by the algorithm itself may be very poor.

For the Dutch Analytics team, represented by CTO Victor Pereboom and Enrique Guiterrez Neri, a data engineer with a key role in the implementation of this exercise, “working together with the Marine & Ports Division of ABB was a great opportunity to validate the performance of our platform and get feedback on its functionality. Collaborating on both the analytics part as well as the deployment shows how well platforms like ABB Ability™ and our own Xenia platform can help in shortening the time to market of the end solution, providing more room for investment in the actual algorithm development itself.”

Finally, for Felix Mutzl, Machine Learning Solution Engineer from ABB Ability™ Analytics team, “this exercise provided an opportunity to help put the analytics framework’s capabilities into practice in a real-world use case. On top of that we enjoyed the fruitful discussions and constructive collaboration with both our colleagues from ABB Marine & Ports as well as the Dutch Analytics team.”

Join us on this journey
In ABB we try to understand the processes that generates data before we apply proper analytical or machine learning methods. This in order to avoid building false models that generate misleading predictions. Statistics and machine learning methods are powerful by themselves, but enriched with domain-specific process identification knowledge, they may provide much stronger results and interpretability. If the data scientists analyzing data from a critical electric motor report very low correlation between the winding temperature signal and the motor current signal, feel free to contact the data engineers in ABB and join our journey. We know from engineering design principles that the current-temperature relation is non-linear, and that checking a simple correlation matrix may lead to incorrect model selection and could result in very poor predictions.

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Polaris icebreaker study
Improving performance and cutting emissions through energy storage

ABB has conducted a study to show how an energy storage system could help improve the overall power efficiency of icebreakers, saving fuel and reducing emissions.

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Vessel-based power systems often come with highly dynamic load profiles, and this is especially true for icebreakers. Traditionally, dynamic load is met by oversized generators running on fossil fuel, which leads to inefficient operation during periods of low demand.

The icebreaker Polaris has been operating for three winter seasons in the Bay of Bothnia. ABB has conducted a study to investigate how an energy storage system could improve the environmental footprint of the vessel while improving fuel efficiency and dynamic response.

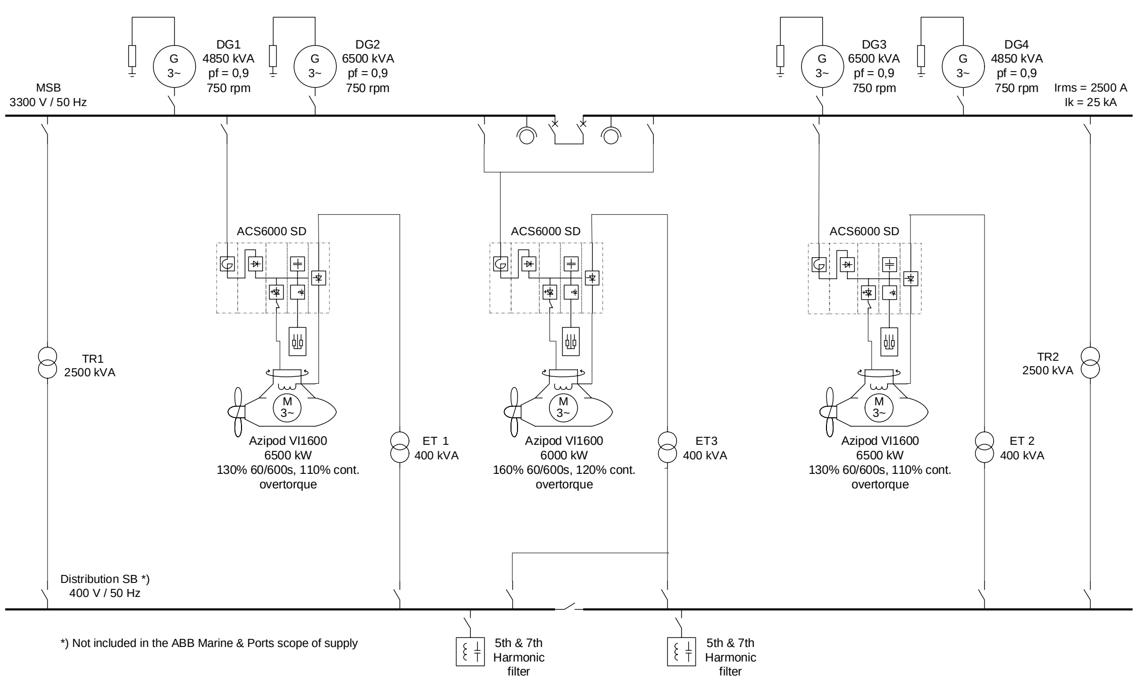

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Figure 1: Single line diagram for Polaris

Polaris icebreaker

Key findings from this study include the following simulation results for LNG and diesel operation, assuming an onboard hybrid battery system:

- For LNG: 38 percent CH_4 reduction, 16 percent less fuel consumption and 46 percent reduction in engine hours
- For diesel: 10 percent reduction in fuel consumption, 36 percent reduction of engine hours

The vessel

Polaris is the world's first LNG-powered icebreaker. The vessel is owned and operated by Arctia Ltd, a Finnish state-owned company. Polaris is built primarily for assistance services in the Baltic Sea, in addition to oil spill response operations. The vessel is equipped with four Low Pressure Dual Fuel (LPDF) engine driven gensets, with an auxiliary engine for producing electricity when the vessel is in port. The electrical power plant's combined output is 22,5 MW. The propulsion system consists of three ABB Azipod® units, two 6,5 MW stern units and one 6 MW bow unit, as shown in Figure 1.

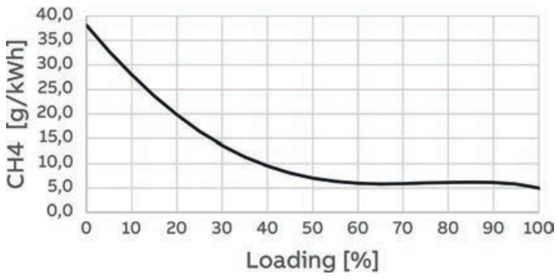

Figure 2: Interpolated Methane slip for dual-fuel engine as a function of generator loading

With a length of 110 m, and a capability to open a uniform ice-free channel through ice field with thickness 1,8 m, Polaris is the most powerful Finnish icebreaking vessel ever constructed.

Environmental challenges of LPDF engines

Stricter emissions regulations for different greenhouse gases (GHG) are leading ship owners to take action. Using LNG as a main fuel is trending as a response to restrictions on NOx and CO_2 emissions, with low-pressure dual fuel (LPDF) engines as a popular choice.[1]

However, one main drawback of LPDF engines, especially when running on gas, is their substantial level of methane slip. Methane slip is the release of unburnt methane caused by incomplete combustion.

According to a measurement study[2], Methane slip comprises 92-97 percent of measured THC emission in LPDF engines. Emissions data available for methane are relatively consistent down to 50 percent load. For the current study, the available data is interpolated as shown in Figure 2, and used as a basis for calculation.

As seen in Figure 2, the challenges associated with methane slip increase at low load operation, as a consequence of poor fuel utilization due to low operational fuel-to-air ratios.

This is an underlying problem in the industry, as CH_4 has a GWP of 25 (25 times higher than CO_2)[3] yet there is no standard regulating methane slip for marine gas engines. However, concerns associated with the environmental effect of methane have lead to increased focus on the issue.

Scope of work

Installation of an energy storage system could contribute to reducing total GHG emissions, primarily CH_4, in addition to reducing fuel consumption and improving the dynamic performance of the system.

In this work, a Matlab file was programmed to investigate the effect of installing energy storage onboard Polaris. The work is based on operational data presented in the following section.

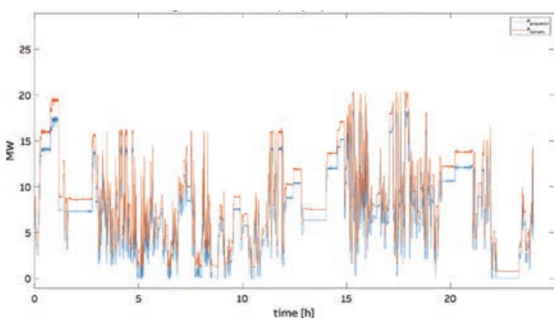

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Figure 3: Genset load and Azipod® propulsion load 16.03.2018

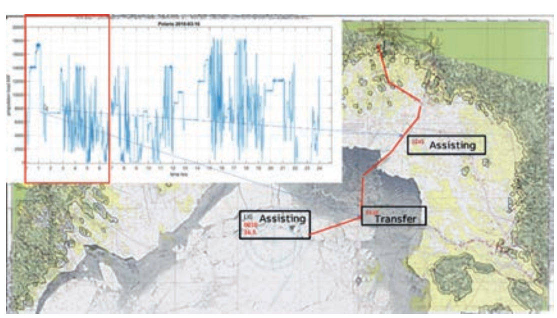

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Figure 4: Load profile in combination with extract of travel over-view the respective day

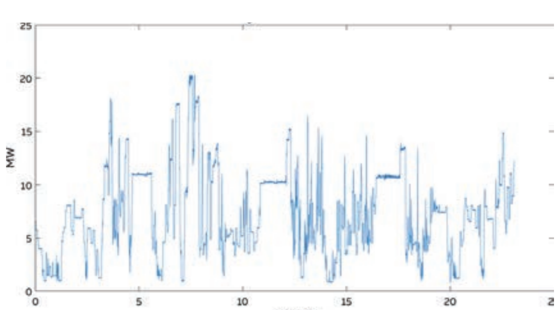

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Figure 5: Genset load profile for 09.02.2018

The overall objective was to simulate a battery system that can absorb large load variations and hence improve fuel efficiency and ramping capability.

Conditions of operation

Polaris is designed for four continuous weeks at sea, though the normal crew change interval is 10 days.

During operation in the Bay of Bothnia, IB Polaris was equipped with an Azipod® ice load measuring system to determine load levels. During the period from January 2017 to May 2019, around 7400 hours were recorded, and about 4,000 hours of operation observed.

For the case study, load measurements for two days have been extracted; one day for diesel operation and one day for gas operation.

Combining the ship log and the load profile in Figures 3 and 4, the following conclusions are evident:

- The generators are mainly loaded by the Azipod® propulsion (as expected) with approximately 200kW vessel hotel load (pumps, fans, light etc.)
- Large load fluctuations during icebreaking
- Large increase in power consumption during assistance

According to Mr. Sampo Viheriälehto, a Master Mariner with extensive experience in operating the Finnish icebreakers, load fluctuations are caused by the control levers being used actively, and the magnitude of the variations depends on the thickness and resistance of the ice. Another key aspect is the fact that the distance between the icebreaker and the vessel being assisted is always required to be 200 meters, and adjustment according to this requirement also leads to power fluctuation.

09.02.2018

On 09.02.2018, Polaris was mainly fueled by LNG. Only 23 hours of operation were available for the day, as presented in Figure 5. For LNG operation the engines do not allow for fast load changes and have an even slower response compared to diesel.

As a consequence the performance of the vessel is slower when running on LNG compared to diesel.

Modelling and simulation

The system and preconditions

The hybrid power system in the model consists of four main generators (the auxiliary generator is excluded), one battery and one main system load, as shown in Figure 6. The battery is charged from the generators, since the vessel usually does not operate close to a harbor. It is worth mentioning that the model is simplified and cannot embody the full complexity of the power system onboard Polaris.

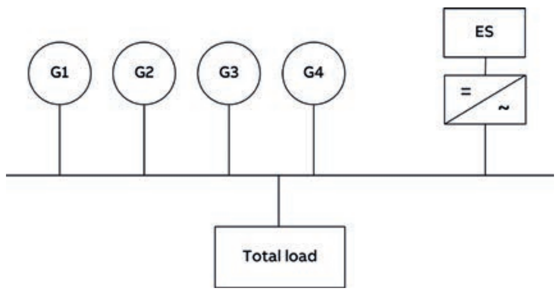

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Figure 6: Power system model

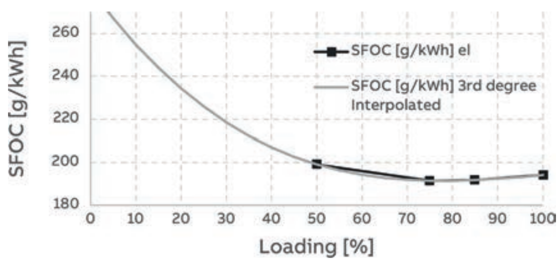

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Figure 7: Adjusted SFOC curves for dual-fuel engine – diesel mode

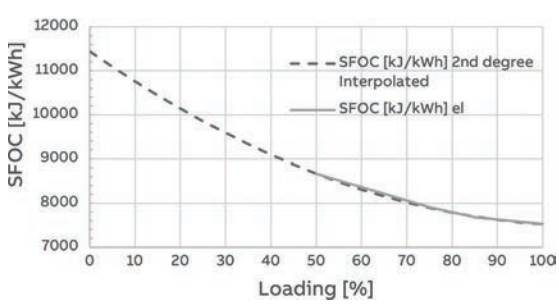

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Figure 8: Adjusted SFOC curves for dual-fuel engine – LNG mode

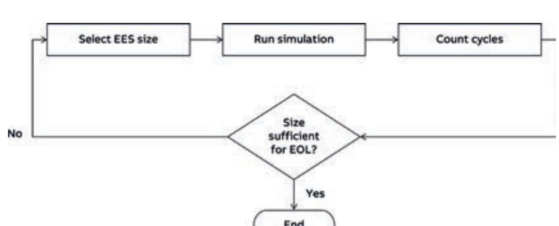

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Figure 9: Conceptual flow chart of sizing philosophy

The gensets are based on characteristics of dual-fuel engines. They can be operated in gas mode or in diesel mode, and the fuel consumption is assumed to follow the SFOC curves shown in Figures 7 and 8 for diesel and LNG, respectively. The Figures are adjusted for genset efficiency and interpolated for loading lower than 50 percent.

Impact of load dynamics

As seen in Figures 7 and 8, fuel consumption increases substantially during low load. Another aspect is the dynamics of the load. A commonly held belief is that having high ramp rates on generator loading negatively affects both the fuel efficiency and the release of greenhouse gasses. Accellerating the engines occurs with lower efficiency and leads to incomplete combustion. There is limited available validated data to quantify this, but based on internal estimates and experiences, a linear correlation between load fluctiations, fuel efficiency and CH_4 emissions has been assumed, resulting in an added penalty for dP/dt on both fuel consumptipon and CH_4 emissions. Maximum limitations are set for load gradient 0.16 percent /s with corresponding penalities of 10 percent fuel increase and 20 percent CH_4 increase.

Selection of energy storage system

The analysis is based on a JP3 battery cell, and the design of the controller is based on a fixed energy storage dimension. The size was selected by means of iteration, as illustrated in Figure 9, to simulate the dynamic behavior of the gensets.

With the assumption of 95 percent charging efficiency, battery capacity was concluded to be 4.5 MWh for these simulations.

Controller design

The simulation model has two tuning parameters: battery capacity and max ramp rate. The battery acts as a peak shaving unit and the ramp rate limiting function limits the dynamic components of the load. A simplified flow chart of the control strategy is shown in Figure 10.

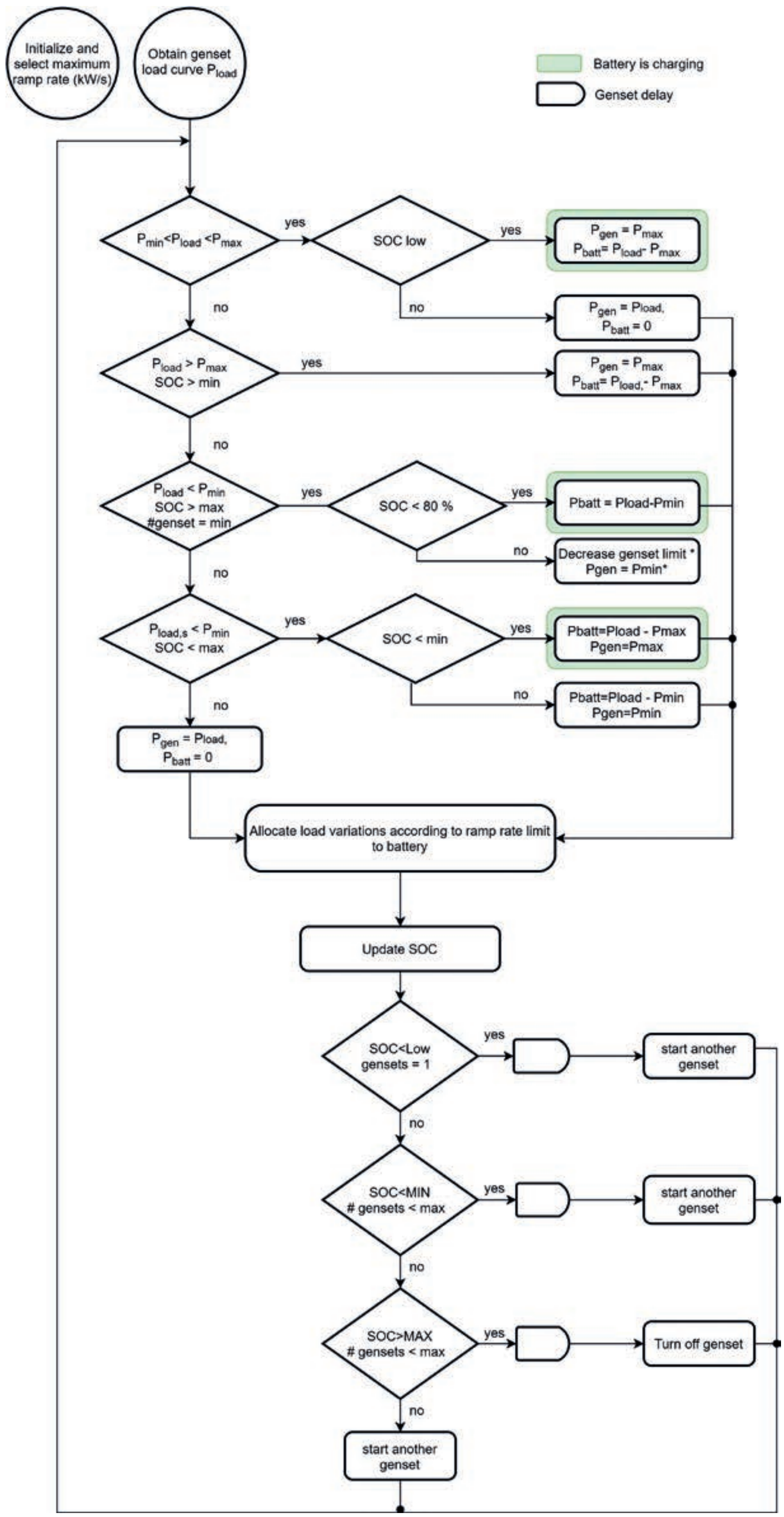

Figure 10: Conceptual flow chart of control strategy

Results and discussion

The simulation resulted in the following savings for the two respective days:

LNG operation

- CH_4 reduction: 38 percent
- Fuel reduction: 16 percent
- Engine hour reduction: 46 percent

Diesel operation

- Engine hour reduction: 36 percent
- Fuel reduction: 10 percent

The simulation of the power system shows how an energy storage system can contribute to supply power peaks during periods of high demand, as well as absorbing load fluctuations. These aspects appear to pay off especially in terms of reduced CH_4 emissions.

The large decrease in engine hours can also be seen as direct savings in terms of maintenance costs.

Installation of energy storage can also improve the dynamic performance of the system, which may have great significance for an icebreaker. Exact quantification of the performance improvement is excluded from the analysis, as slow engine speed already limits the load profile used in the simulation. Energy storage can nevertheless provide instantaneous power and hence also provide ramps where the engines fall short.

Figure 15 illustrates how a battery can absorb load fluctuations that are faster than a selected range, below simulated for the range 200 kW/s.

Simulation shows reduction potential for both fuel consumption and CH_4 emissions when gensets are operating more efficiently, and when the dynamics of the load are decreased. High ramp rates on generator loading are known to affect fuel efficiency negatively, but there is limited data to quantify this. It may therefore be reasonable to believe that savings potential is even greater in the transformation to a more stable load profile. This could be the subject of further study.

Spinning reserve

As the minimum State of Charge (SOC) is set to 20 percent of installed capacity, there will always be a certain amount of energy available in case of a generation outage. The range of SOC can consequently be adjusted accordingly. This contributes to increasing redundancy and can allow generators to work at optimum power output, without the need to keep additional genset capacity for spinning reserves.

The impact of battery choice

A larger battery could provide more savings for two reasons: more efficient energy management system, and lower losses due to lower c-rate. A battery cell with enhanced cycle life and charge and discharge capability could on the other hand enable a smaller battery. Depending on the choice of battery and the control strategy, an energy storage system could be optimized further in terms of sizing, as a trade-off between cost and performance.

Conclusion and next steps

Despite the limitations of the model, it is evident from the simulations that installing a battery can play a positive role in the power system of Polaris. In particular, reduction of both methane slip and the number of running hours on the engines should be emphasized. Next steps that could be further developed include:

- Quantifying the actual impact of dynamic load
- Tuning of the optimal energy storage system solution

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Sources:
1. Methane slip from gas fueled ships: a comprehensive summary based on measurement data
2. Methane slip from gas fueled ships: a comprehensive summary based on measurement data
3. https://www.epa.gov/ghgemissions/overview-greenhouse-gases#CH_4-reference

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Litterature:
Optimal Operation and Sizing of Energy Storage System for a Ship Electrical Power System

Methane slip from gas fueled ships: a comprehensive summary based on measurement data

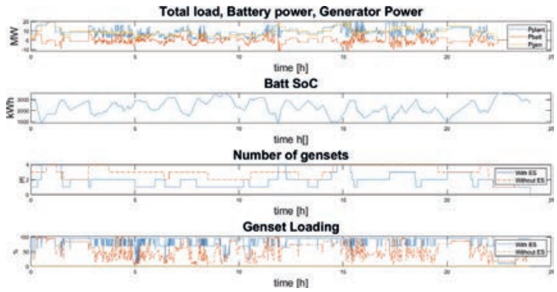

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Figure 11: Simulation results for 16.03.2018 – diesel operation with 4.5 MWh energy storage in-stalled

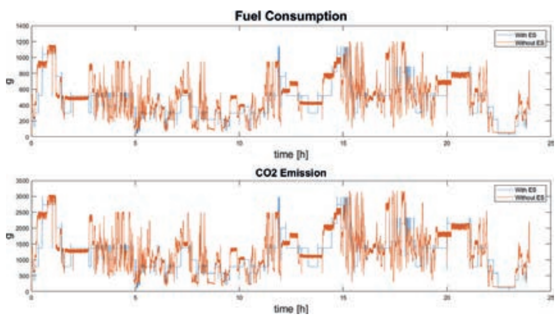

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Figure 12: Simulation results on fuel consumption and CO_2 emissions for 16.03.2018 – diesel operation with 4.5 MWh energy storage installed

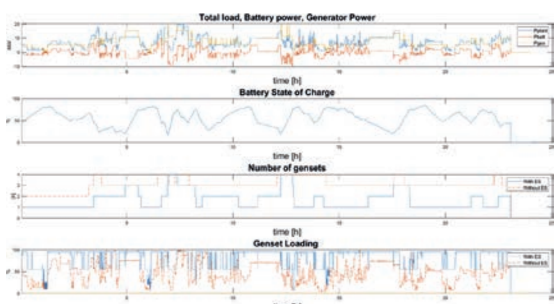

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Figure 13: Simulation results for 09.02.2018 – LNG operation with 4.5 MWh energy stor-age installed

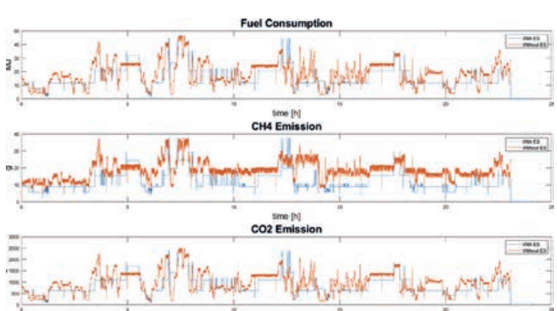

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Figure 14: Simulation on fuel consumption, CH_4 and CO_2 emissions for 09.02.2018 – LNG operation with 4.5 MWh Energy Storage installed

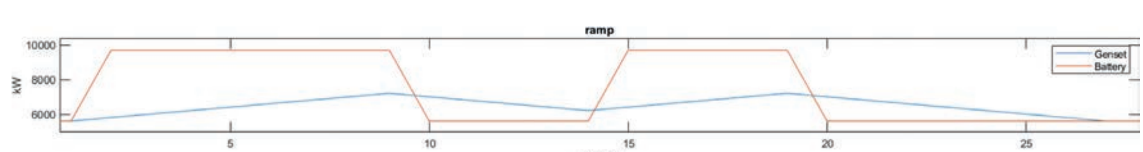

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Figure 15: Illustration of how a battery can "smooth" the genset power curve

Best icebreaking practices

Icebreaking allows the nations of the North to maintain a vital, continuous supply of goods and raw materials through the cold season.

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SAMULI HANNINEN
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Icebreakers in the historic context
In the early days, icebreakers were steam powered. As early as 1933, the first diesel electric icebreakers were introduced, though diesel electric propulsion remained rare outside the icebreaking sphere for decades. With the passing years, diesel electric propulsion has gained momentum. The diesel electric powertrain offers many advantages over traditional mechanical diesel shaft line propulsion, including enhanced power management at speed and more reliable dynamic power handling.

Science, cargo transport or line icebreaking?
In icebreaking, the general operations are generally divided between scientific operations, cargo transport and assistance of merchant marine vessels. Scientific operations are subject to the same environmental conditions as assistance, but without the time pressure of line icebreaking. Indeed, the distinction between icebreaking for science and assistance can be found in the different requirements for efficiency. In line icebreaking, the number of vessels assisted over a period of time is a key parameter. Different sets of realities dictate the different icebreaking duties. In some countries, the annual number of icebreaking assistance cases is less than hundred. In countries dependent on icebreaking, assistance is an ongoing operation, resulting more than 3,000 cases annually. From an operating point of view, there are many similarities between line icebreaking and scientific operations. In both cases, vessels are sometimes required to face consolidated hummocks and ridges. This operational requirement also extends to icebreaking cargo vessels proceeding independently through ice-infested waters.

Responsibility for other vessels
In scientific research, the timeframe for planning the voyage is relatively long. In cargo transport, the charter of goods is always set in a particular time frame. Despite their dissimilarities, there is an even bigger difference between vessels used for these tasks and those used for line icebreaking. A vessel with responsibility only for its own operations demands different capability than a line icebreaker managing ports and vessels, pilotage and VTS functions together. In ship design, it is also important to distinguish whether the vessel will be primarily engaged in assisting other vessels or attempting to complete a voyage independently.

Azimuth thrust
The handling performance of ships remained in many respects static until the introduction of the azimuth thruster. Azimuth thrust increases the efficiency of icebreaking assistance by enabling the ship's main engine power to be directed 360 degrees. This freedom of power vector application has brought profound change to icebreaking. The main categories in azimuth thrust are mechanical thrusters and electric gearless thrusters. With mechanical thrusters, the electric or diesel motors are located inside the ship's hull. In this configuration the power is transmitted via axles and bearings to the propeller. With the electric azimuthing thruster, thrust is generated in the pod unit by an electric motor. The electric pod does not require gears to transfer power.

—
Consolidated and ridged ice field

These features have made the electric propulsor the leading technology of choice in icebreaking. It has also allowed the unit size to grow into the 20MW range.

Line icebreaking principles
Line icebreaking can be roughly divided in four distinctive tasks, though the sequence may vary depending on direction of traffic. Assuming a vessel is in-bound to port from sea, the operation starts with variable sea ice conditions and moving ice fields at sea. Often the vessel is confined in ice, requiring the icebreaker to first cut her loose. In high wind conditions, the ice field also has a significant pressure component preventing vessel movement. Secondly the vessel must be assisted to the fairway area. In the fairway, assistance is limited by draft and buoyage. When the convoy reaches the port entrance, the icebreaker terminates assistance and port icebreaking assumes responsibility. Azimuth propulsion can play a key role in all the above situations by reducing the time needed for ice management.

Sea ice conditions present icebreaking challenges
Sea ice conditions vary greatly and are constantly changing, presenting icebreaking crews with unique challenges. For example, sea ice in the Arctic is often a mix of drift first-year ice with multiyear ice inclusions. Ice at sea is in constant motion, and movement tends to range from 0,1Kts to 1,1kts . When the ice is packed against a land mass or a fixed ice pack, the combination of wind and ice movement creates ice pressure. This pressure in turn forms different ice features. In a level ice field, the pressure begins to crack and bend the ice, creating ridges and hummocks. If the ambient air temperature is well below freezing, the hummocks consolidate and become very difficult to move. At the ice edge where swell and wind work against the ice, the result is different. Here drift ice is ground into shuga and brash ice barriers. If temperatures are well below freezing, the brash ice barrier eventually consolidates into floes that are very difficult to impact.

Track creation width
An icebreaker with solid axles creates a track as she forces through the ice. The track width is defined by vessel breadth, ice quality, ice pressure and direction of travel in relation to ice movement. In fast ice with low ice pressure, the track may be 1.5 times the breadth of the icebreaker. In heavy ice pressure the track closes just seconds after the icebreaker has passed. For a merchant vessel to be able to follow the icebreaker the track

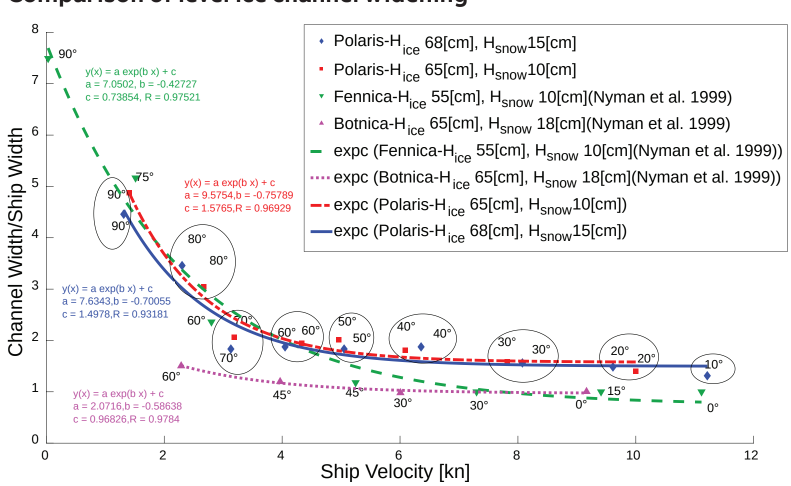
must be sufficiently wide. As the track closes, the speed of the assisted vessel decreases and the vessel finally comes to a stop. To increase track width, the breadth of the icebreaker must be increased. This however has practical upper limits. Power requirements and fuel consumption grow with the increased size of the icebreaker. Azimuth thrust offers a solution for this problem, enabling the ship's thrust vector to be directed not only aft, but also to the sides of the ship at an angle. This creates a power vector moving the icebreaker forward, but also creates a wider track. In relative terms it becomes feasible to assist larger vessels and operate in difficult ice fields with increased efficiency. It is often critical to achieve increased track width in order to conclude assistance without stopping. Azimuth thrust enables increased track width and improves assisting efficiency.

A wide channel can also be made by steering the ship at an approximately 40-degree angle sideways. This oblique icebreaking is possible with icebreakers equipped with aft and bow mounted azimuth thrusters. Oblique icebreaking creates an ice channel at least twice the width of the ship.

Cutting vessels free

Cutting loose a vessel beset in ice requires operations at close quarters. In heavy ice conditions this is done with high power output. Together, these factors contribute to a high risk of collision. Azimuth thrust increases the maneuverability of the icebreaker many times. Turning circles are decreased and overall control is increased.

Comparison of level ice channel widening



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Track creation width in ice trials with vessels equipped with azimuth propulsion at different thrust vector angles (10º to 90º). Courtesy of Taimuri and Kujala.

Ice pressure can create dangerous conditions where ice floes begin to climb up the side of the ship. In these conditions the icebreaker makes safety circles around the beset vessel to alleviate pressure. In these conditions the increased maneuverability due to azimuth thrust enables making closer and faster safety circles.

The mode of operation differs between icebreakers with solid axle lines and azimuth thrust, when cutting ships loose. With solid axles the icebreaker moves along the beset ship at very close quarters and cuts close in front of her bow. At the moment of passing, the icebreaker instructs the beset vessel to make full ahead. When in front of her bow, the two begin to move as a convoy. The icebreaker leads the way and adjusts the distance between the vessels according to ice conditions. When the ice pressure increases, or ridges form choke points, the vessel is escorted at very close proximity to the icebreaker, sometimes only a few meters apart. Azimuth thrust changes these sequences by allowing the icebreaker to pass by and flush the ship free by manipulating the thrust vector toward the beset vessel. By eliminating the need to move in front of the bow, it is also possible to flush loose multiple vessels sequentially. Convoy assistance with azimuth thrust also differs from the example above. With azimuth thrust, the icebreaker can adjust to the prevailing ice pressure and choke points incrementally by spreading the thrust vector. This allows greater distance between the vessels, improving safety and reducing the risk of collision in case of a sudden stop due to unexpected ice features.

Azipod® full-scale ice load measurement

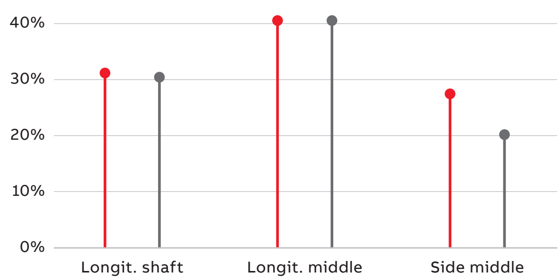
The first azimuthing podded propulsors for ice going ships were launched in the 1990's. Due to the novelty of the concept, no information or guidance about azimuthing propulsor ice loads was available. Ice loads needed to be measured in order to verify dimensioning loads.

The first measurements showed that dimensioning was conservative, as expected. This does not mean that structural dimensioning should be lightened. Ice loads vary greatly depending on ship type and operation area. Over the years, propulsors in different ice going ships with high ice class – supply vessel, cargo vessel, and icebreaker – have been instrumented for ice load measurements.

Load calculation and dimensioning methods including power and propeller torque usage can be verified to cover a wide range of propulsors in different ships, providing solid tools to develop reliable higher power equipment.

The latest ice load measurements were conducted on the Finnish icebreaker Polaris' propulsors. The ship is equipped with a three-pod solution, with 6 MW Azipod® unit at the bow and two 6.5 MW units at the stern. Polaris is the first icebreaker with a propulsor unit at bow, and offers excellent opportunities to compare ice load distribution between stern and bow propulsors.

Polaris has been in operation in the Bay of Bothnia for three winters, 2017-2019. Ice conditions were so mild in 2020 that Polaris was not required to perform icebreaking duties. Operational experience thus far indicates that the maximum measured loads for bow and stern propulsors were about 40 percent of design loads.



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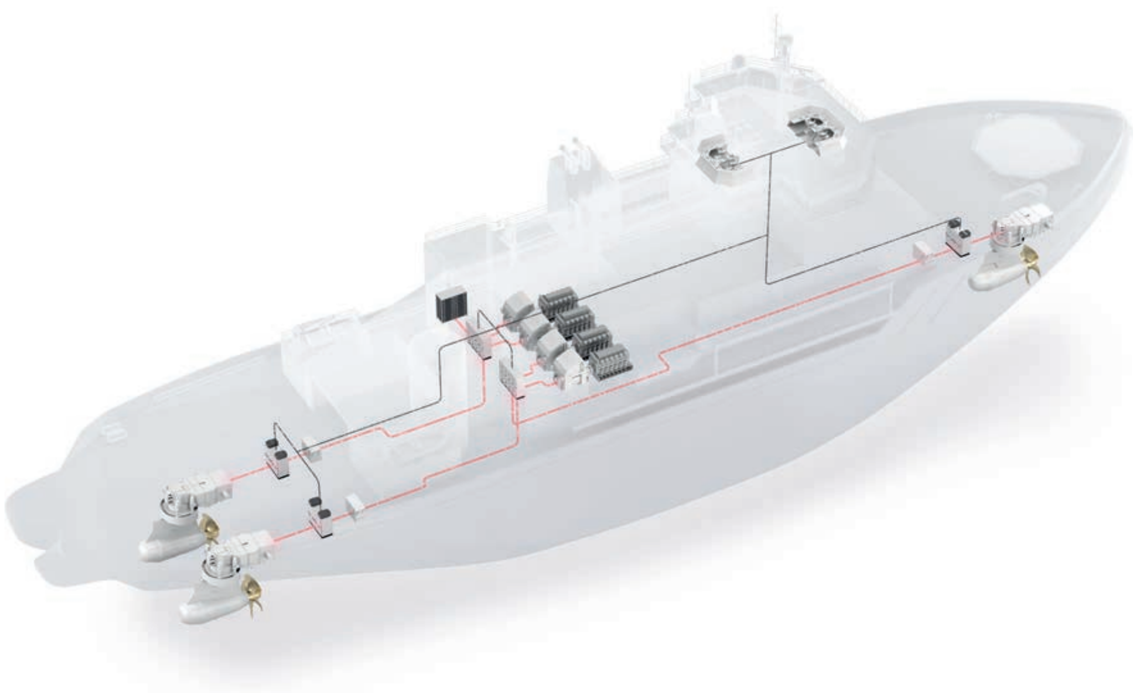
Measured loads compared to design loads
● Stern
● Bow

Design ice loads for the bow propulsor were 25 percent greater than for the stern propulsors, which corresponds well to longitudinal measured loads. Bow propulsor ice loads are slightly higher for longitudinal direction that for stern propulsors, and stern propulsor side loads are correspondingly higher for side direction. This is as expected, since stern propulsors are operated more often in different steering angles and receive ice hits from the side. The bow propulsor is mainly at zero angle when proceeding in ice at high speeds. Increased design loads for bow propulsor side ice load are therefore not necessary.

ABB ice load dimensioning principles for the Azipod® propulsor has been well proven, with 30 years of ice operation. In addition to full-scale load measurements, dimensioning has proven to be safe, since no ice-induced damage of propulsor or propeller has been documented.
Based on the long-term measurements, it can be concluded that a Polaris-type icebreaker can operate without speed or other operational restrictions in all Baltic Sea ice conditions. This includes ramming operations in ridged ice fields in the Bay of Bothnia.

Another article in this edition of Generations reviews onboard energy storage system for icebreaking (Title, page no.). Long-term measurement data from IB Polaris were further used to simulate the benefits and enhanced operational performance with the aid of a battery pack.



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Schematic layout of Azipod® propulsion arrangement onboard IB Polaris

The development of Polaris was closely followed by several icebreaker operators. After Polaris, the Russian energy giant Gazprom Neft ordered two icebreakers “Alexander Sannikov” and “Andrey Vilkitsky” based on a similar ship concept. Gazprom Neft operates the Noviy Port oil fields on the Yamal peninsula in demanding ice conditions. To support operations close to the Arctic loading terminal, two highly maneuverable icebreakers were needed, and the Polaris concept proved to be a perfect fit. Power was increased to two 7.5 MW Azipod® units in the stern and a single 6.5 MW Azipod® unit in the bow. The ice class was also increased to Russian Maritime Register of Shipping Icebreaker 8, the second-highest RMRS IB class, corresponding to IACS PC2. Both vessels were delivered in 2018, and operational experience thus far has been highly positive.

The North Pole and beyond

The Norwegian Coast Guard vessel KV Svalbard is the first ever Azipod® powered ship to reach the North Pole, another milestone demonstrating the capabilities vessels with Azipod® propulsion.

In August of 2019, KV Svalbard, built in 2001 and equipped with twin 5MW Azipod® icebreaking units, became the first Norwegian vessel to sail to the North Pole. The ship travelled through packed polar ice at speeds as high as six to seven knots as part of an international scientific expedition, the Coordinated Arctic Acoustic Thermometry Experiment (CAATEX), led by the Norwegian non-profit research foundation The Nansen Center.

Latest developments

The changes in ice concentration and reach in the Arctic have allowed for increased vessel traffic. Where many operations were not feasible in the past, they now are. This is the result of ice conditions lessening in severity, and technology moving forward. The VI series Azipod® has been a key factor in enabling Arctic shipping to grow. A good example is found in Arctic offshore oil and gas activity. To be economically feasible, vessels must be able to operate without continuous icebreaker assistance. Azipod® VI has provided the necessary bollard pull levels, but perhaps more importantly the capability to navigate the vessel stern-first through consolidated ridges and hummocks.

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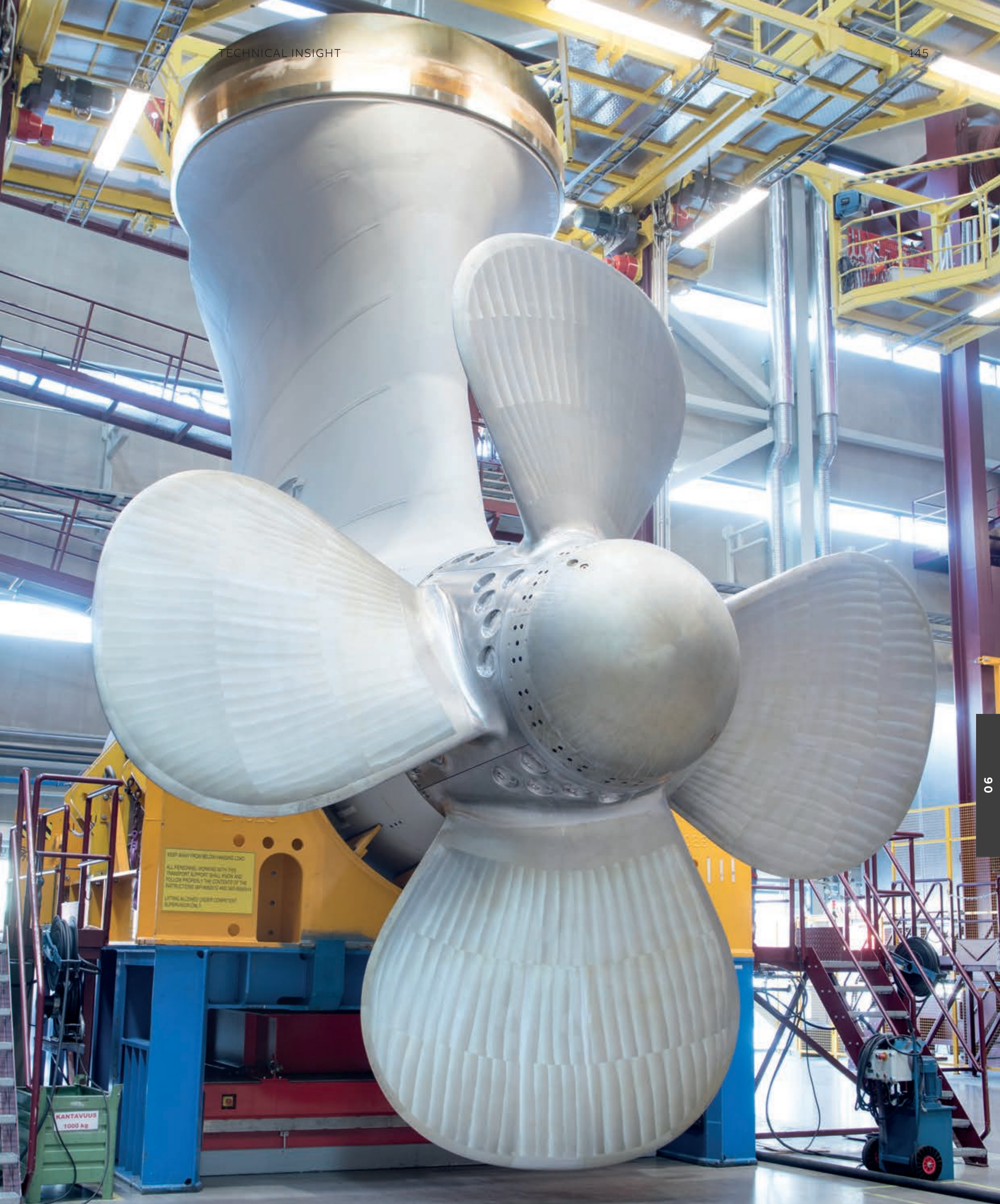
Azipod® VI propulsion unit


KANTAVUUS
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System health management boosts intelligence of Chinese polar research vessel

The Xue Long 2 (XL2) polar research ship (H2560) is the first independently built polar research icebreaker in China. It is one of the most advanced polar research icebreakers in the world, and also the first intelligent ship in the world achieving China Classification Society (CCS) intelligent notations.

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CN LPG AC R&D Manager
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EVAN-FEI E
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The delivery of the ship not only filled in the blank of major Chinese equipment supply in the field of polar scientific research, but also marked a breakthrough in field support and support capacity of China's polar research, as well as a milestone in the development of ship intelligence. XL2 was selected as one of the top 10 Chinese significant country projects in 2018. ABB Marine & Port China provided the 'electric propulsion health management system' for XL2. As the core component of vessel's intelligent engine room, the system helps the ship to realize intelligent power and propulsion equipment operation monitoring, diagnosis and maintenance advice.

Advancement and intelligence proposition
As one of the world's most advanced polar research vessels, XL2 was designed to perform demanding work in global non-restricted waters, such as polar scientific research, polar supply and ice region rescue.

Advanced vessel power and propulsion system
To meet the tough operational demands, XL2's power and propulsion system has the following characteristics:

- Double-ended ice-breaking capability
- PC3 level ice breaking capability to navigate at 2-3 kn in ice regions with 1.5 meter ice
- 360 degree fixed-point rotation

In acknowledgement of their good reputation and leading technology and products, ABB Marine was selected to supply the whole power and propulsion system package for XL2. The scope includes:

- 4*MVDG + 2*transformer + MVSB
- 2*(Azipod® VI propulsion + 24p converter + 2*transformer)
- 2*BT

Operational intelligence
Besides advanced power and propulsion equipment, the owner also had enhanced requirements to further guarantee the operational safety and reliability of the vessel and onboard equipment:

- Real time on board and on shore monitoring and assessing of main power and propulsion equipment
- Timely technology support and maintenance advice from suppliers
- All machinery data managed in an integrated platform

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The polar research vessels Xue Long 1 and 2

- Applying for the CCS's intelligent engine room and integrated platform approvals and acquiring the i-Ship (M) and i-Ship (I) notations
- Minimizing environmental impact

Health management system
To help the owner realize intelligent operations, ABB Marine presented the Health Management System (HMS) solution based on its dedicated cutting-edge remote diagnosis and assessment technologies and products.

System architecture
The HMS is composed of remote diagnosis system and Asset Optimizer. Its structure can be divided into four levels:

- On shore operation – ABB Ability™ Collaborative Operations Center
- Onboard comprehensive user station – Integrated platform/ ABB Ability™ Remote Diagnostics System UI & AO
- Field data process station – ABB Ability™ Remote Diagnostics System cabinets
- Field data acquisition station – DAUs & sensors

Its functional scope covers:

- Propulsion drive
- MV switchboard
- Azipod® propulsion
- Main machines, including generators and thruster motors

System functionality
HMS has two classes of functionality: basic conditions monitoring and enhanced conditions assessment.

Basic functions:

- Condition monitoring onboard
- Failures detection and alarm onboard

Enhanced functions:

- Condition grade assessment
- Failures causes analysis
- Failure treatment advice
- Periodical comprehensive health status report
- Condition-based maintenance advice
- On shore remote condition tracking
- On shore remote support

Verified by the initial voyage to the South Pole
From October 2019 to April 2020, XL2 performed its first polar research task, together with XL1. The voyage covered around 35,000 kilometers, of which about 5000 kilometers were in ice areas. During the voyage, XL2 carried out long term ice-breaking navigation and multiple polar scientific research operations. The HMS effectively assisted the operators of XL2, both on board and ashore, in accomplishing the relevant machine condition monitoring, critical data recording, status analysis and assessment in diverse operational profiles. The performance of the HMS earned the praise of the customer.

The success of the voyage not only further verified the reliability and performance of ABB products and the intelligent solution's validity, but also pioneered intelligent electric propulsion, and consolidated the industry-leading position of ABB's digital solutions and products.

Shore connection
Improving ship efficiency and cutting harborside emissions

Mounting pressure from regulatory bodies and the general public to cut emissions in ports has driven shipping to consider shore power connection.

MARCUS MARTELIN
VP Service Product
Group Manager
Electric Systems
ABB Marine & Ports

In a ‘smart port’, when a ship docks, it is also plugged into an onshore energy supply, allowing electrical onboard functions to run while the diesel engine is shut off. This cuts out harmful emissions and reduces noise pollution in sensitive, often densely populated harborside areas. In some circumstances, landside power supply can be used as ‘charge’ to replenish a shipboard energy storage system, with the resulting battery power available for short distance operations, whether for end-to-end ferries or for emissions-free propulsion in port or in protected waterways, for example.

To understand the value of shore connection in more tangible terms, it is helpful to compare the fuel consumption of a typical diesel-powered commuter ferry with that of a vessel modernized to draw on shore supply. If a conventional ferry consumed 84 liters of diesel fuel per hour, its battery-powered equivalent would, of course, consume zero. However, a ferry adapted to run on hybrid power could consume as little as 17l/h, depending on the operational profile.

As a leader in electric shipping and smart port technology, ABB Marine & Ports offers comprehensive shore connection solutions comprizing state-of-the-art infrastructure both onshore and on board. Systems are compliant with international regulations and includes high- and medium-voltage switchgears, transformers, frequency converters, control and protection systems and more.

In conjunction with these solutions, ABB provides a wide range of services, such as remote monitoring, planned maintenance for ABB installed base and third-party systems, system studies, project management and training, as well as round-the clock access to its global support network.

Shoreside installation
With an important role to play in reducing the enivironmental impact of global shipping, shore connection has received backing from organiations such as the European Union. For example, EU Recommendation 2006/339/EU promotes the implementation of shoreside electrical facilities, while EU Recommendation 2003/96/EC proposes the subsidization of shoreside power supply for ships through the cancellation of electricity taxes.

At the same time, discrepancies in frequency between ship and shore are driving demand for more intelligent landside solutions.

ABB’s onshore offering comprises transformers and frequency converters to synchronise shoreside power, voltage and frequency with those of the vessel’s onboard system. Also included are

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Holland America Line has multiple ships retrofitted with ABB shore connection solution

connecting cables and berth terminals with capacity for several ships. The solutions are suitable for container terminals and city harbours, with power ratings to suit even the largest ports.

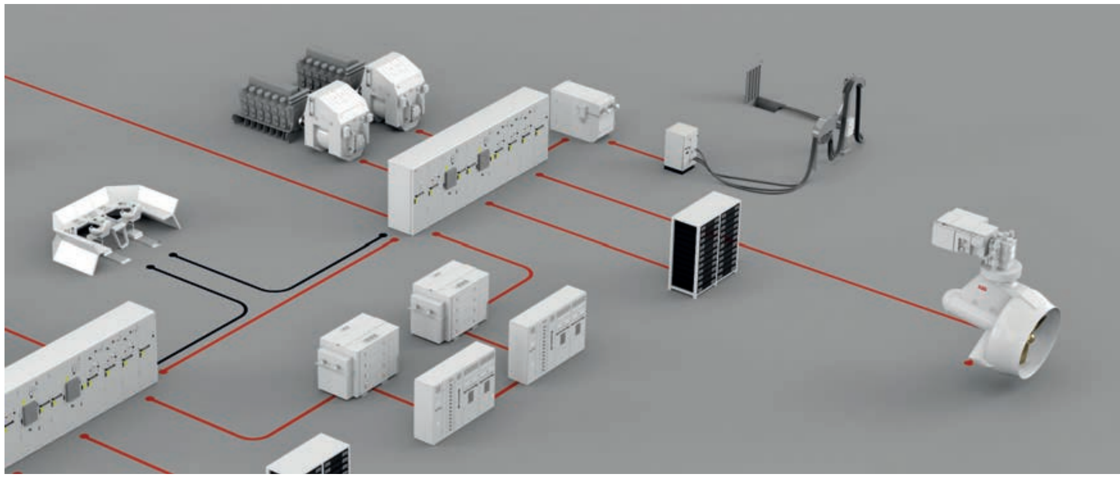
They cover the entire chain from the substation receiving electricity from the local network to the power outlet at the dock. Furthermore, all major components can be accommodated within compact buildings or containers designed to blend into the surrounding environment.

ABB delivered the world's first shore power supply system to the Swedish port of Gothenburg in 2000. Other ports to have implemented high voltage shore power supply systems include Karlskrona, Gothenburg and Ystad, Sweden; Antwerp and Zeebrugge, Belgium; Rotterdam, The Netherlands; Lübeck, Germany; Oulu, Finland; Delimara, Malta; Duqm, Oman; Los Angeles and Seattle, United States; Vancouver, Canada; Jurong Singapore; and Dalian, China. It is currently engaged in projects to equip the ports of Incheon, South Korea and Tallinn, Estonia with shore power systems.

Shipside installation
ABB's shore power supply solutions allow a vessel's energy load to be transferred to the shoreside source in a secure, automated manner, without disruption to onboard services. This means that the ship's auxiliary engines can be shut down for the duration of its harbor stay. Emissions into the local surroundings are thereby eliminated, enabling compliance with environmental regulations set by authorities such as the International Maritime Organization, California Air Resources Board, the EU and individual governments.

In addition, ABB shore connection solutions cover all necessary electrical and automation infrastructure on board and can be used for retrofits and newbuilds. They are delivered on a turnkey basis, with support in procurement, project management, system studies and calculations, engineering, installation, commissioning and testing.

Installation and connection in depth
Onboard shore connection is available in the power range 0–20 MW. Smaller vessels such as ferries typically use low-voltage solutions, while larger vessels such as cruise and container ships require higher voltages. ABB offers shore connection solutions in low voltage (less than one kilovolt in alternating current power and less than 1.5kW in direct current power) in accordance with IEC/IEEE 80005-3 LVSC general requirements – and high voltage (between 6.6 and 11kW) in accordance with IEC/IEEE 80005-1 HVSC general requirements. Sockets and plugs are standardized for roll-on/roll-off vessels and passenger ferries



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Basic shore connection shipside installation on a large vessel

(11kW), container ships (6.6kW) and cruise ships (6.6kW, 11kW). Standardized cable management systems are available for these vessel types.

Installations vary depending on the kind of solution being deployed and on which type of vessel. For Azipod® electric propulsion systems on cruise ships, for example, cable sockets are mounted in the front part of the cabinet. A shaft line system on a container vessel involves an onboard cable drum lowering the cable down to the quay for onshore termination. Meanwhile, the shaft line system for ro-ro and ro-pax vessels entails an onboard transformer converting the power from high to low voltage.

In general, the sequence for connecting and disconnecting a vessel to shore power is as follows: the ship arrives in port, power and control cables are connected, and the last running engine is synchronized with the landside power grid. After the shore connection circuit breaker is closed, the generator is offloaded, and the engine is stopped. Before the vessel departs, the first engine is restarted and synchronized with the onshore power grid. Once the load has been transferred to the generator, the shore connection reopens, power and control cables are disconnected, and the vessel is ready for departure.

Shore connection system components
Essential components of a high-voltage shore connection system include a high-voltage shore connection panel, an automation interface between shore and ship, a main switchboard feeder panel, control and protection equipment, safety circuits and an incomer panel.

The high-voltage shore connection panel is developed in accordance with the rules of major classification societies. It features a finished cabinet solution with power and control modules. This may come equipped with either cable sockets in the front or openings for cable entry through the cabinet floor.

Automation interfaces are standardized based on the ABB platform and also comply with guidelines laid out by major classification societies.

Installation of the main switchboard is carried out on a case-by-case basis. It may be fitted as part of the vessel's existing main switchboard with an additional cubicle and circuit breaker including control and protection devices. Alternatively, a 'generator panel' can be connected to the ship's main switchboard via fixed cables or bus bars.

Optional components include:
- Power management system with integrated shore power system
- Step-down transformer to match shore voltage with ship voltage
- Human-machine interface to operate the shore power system
- Cable management system (typical for container vessels)
- Automatic voltage regulator, i.e. Unitrol® 1020
- Governor system, i.e. DEGO IV
- Protection coordination study upgrade

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Color Line has fitted five ships with ABB shore connection solutions enabled in four ports

Shore charging for electric vessel operations
As noted earlier, shore charging solutions are a vital component in the smart-port environment – allowing emissions-free propulsion in protected areas – and need to be designed and delivered in conjunction with the rest of the system. They can take one of two basic forms depending on requirements: manual cable connection and automatic connection.

Manual cable connection
Manual cable connection is appropriate when normal operations do not require fast battery charging. Low-voltage, manual plug-in solutions are available up to 600 amperes, which typically allows a transfer power of up to 450 kilowatts. It is divided between night-time and daytime charging.

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Corsica Linea ferries are fitted with ABB shore connection solutions

Night-time charging is when the battery is connected to the power supply overnight, leaving it fully replenished ahead of daily operations. In daytime charging, the battery receives power in shorter intervals throughout the day. How the two methods are combined influences the dimensions of the battery and transfer line.

Maximizing the daytime charging current often means deploying longer transfer lines, components and batteries (batteries are oversized to account for cyclic charge/discharge current). Meanwhile, placing more emphasis on overnight charging increases total battery capacity requirements or calls for hybrid operations, with batteries used in parallel to the generators.

Automatic connection
Available in both low- and medium-voltage solutions, automatic connection provides a power range of up to 20 MW, making it preferable for fast charging. It allows vessel operators to maximize charge during short harbor stays. It also keeps crew involvement to a minimum. However, automatic connection can be significantly more expensive and careful analysis is required to determine whether a connection is really feasible.

Conclusions
With environmental regulations becoming ever-more stringent, shore connection is garnering wider attention – and with good reason: synergy between shore and ship improves the efficiency of vessels but also, crucially, helps to protect harborside environments.

ABB Marine & Ports offers landside and onboard solutions encompassing every step in the shore-to-ship chain. These enable vessels to run auxiliary functions wholly on shore power while berthed, negating the need for bunker fuel in shoreside operations. They also optimize the battery-charging process so that electric and hybrid ferries can comply with regulations while operating in sensitive areas.

A considerable number of smart ports are already active around the world, and many more are in the planning or development stages. As the technology becomes more widely established, ships will become more efficient and ports will become cleaner, benefiting everyone from shipowners and electricity suppliers to dock workers and harborside residents.

Onboard Microgrid
Simplified power system integration

Offering a wide range of power and system configuration options, the first delivery of ABB Onboard DC Grid™ took place in 2013. It has since proven to be a highly effective solution, providing enhanced performance, improved efficiency and a high level of system safety.

MATTI LEHTI
Product manager
Onboard Microgrid
ABB Marine & Ports

Onboard Microgrid was introduced in 2019 to provide the benefits of hybrid DC-power systems and electric propulsion to smaller vessels serving inland waterways and short sea shipping. The product enables the entire DC-power system and its controls to be housed in one or two enclosures of very low height and with a limited footprint.

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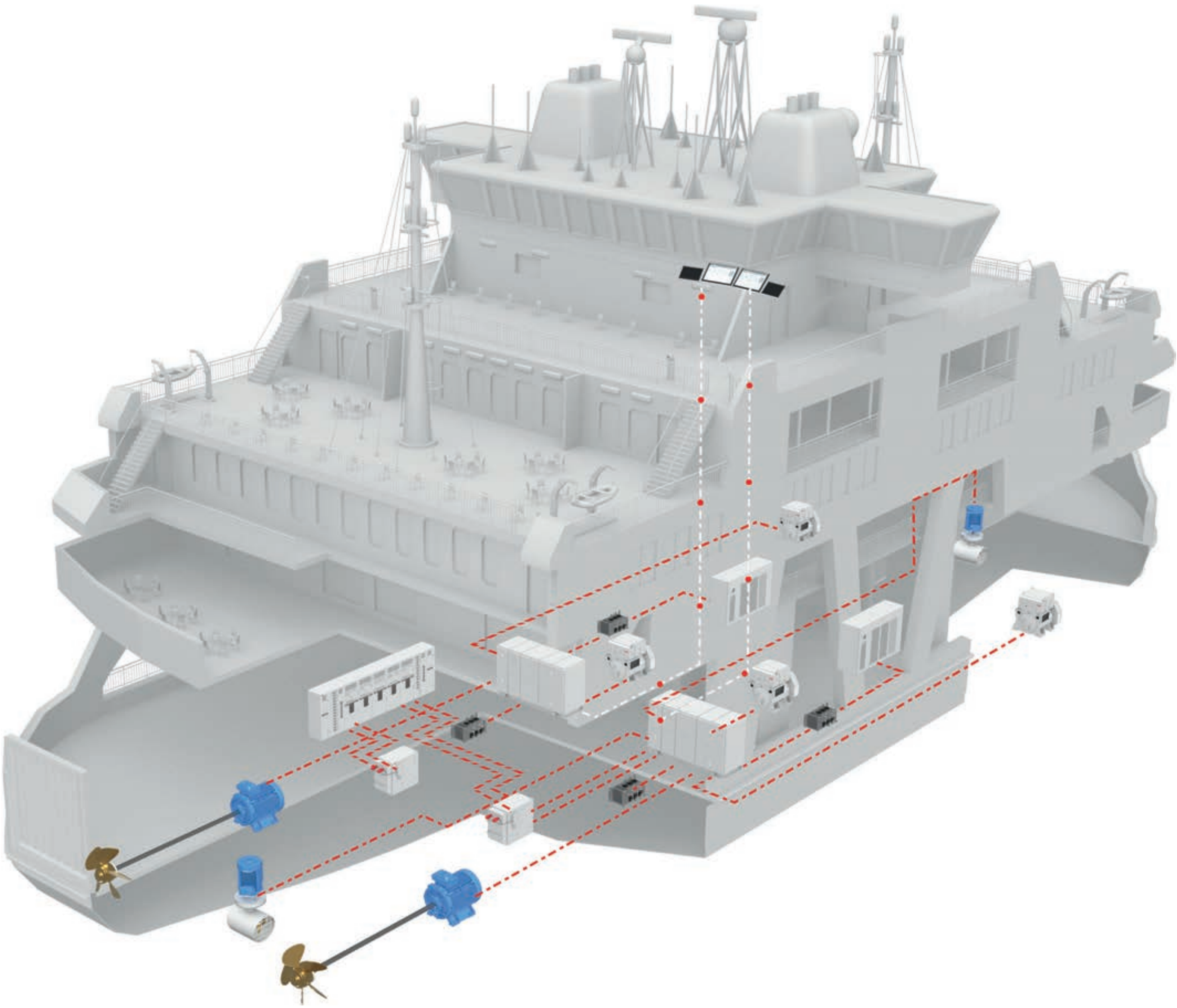
HMI screens for mode selection / system overview and PEMS / consumer status

The core of the Onboard Microgrid solution is the drive cabinet OMD880LC, which houses an electric propulsion drive, AC-distribution power supply, and four optional power sources or consumers, all connected to a common DC-bus. These may be configured as diesel generator, shaft generator, shore connection, battery energy storage or variable speed motor drive for thrusters or other consumers. Frequency converter modules in the drive cabinet are ABB HES880-type. The water-cooled HES880 is designed for harsh environments in applications like marine propulsion, mining machinery and other heavy equipment. Maximum propulsion power from a single inverter module exceeds 600 kW, and higher power or redundancy may be achieved by utilizing two units to run a propeller. The system is well suited for double-ended ferries, yachts, sailing yachts, pushboats, tugboats, work-boats, river vessels and PTO/PTI-systems.

The integrated control system includes all functions required to operate the vessel’s machinery through a single HMI. Power and energy management functions support diesel generator sets, battery energy storage systems, shaft generator and shore connection as energy sources. These may be connected to a single OMD-unit or shared with two units.



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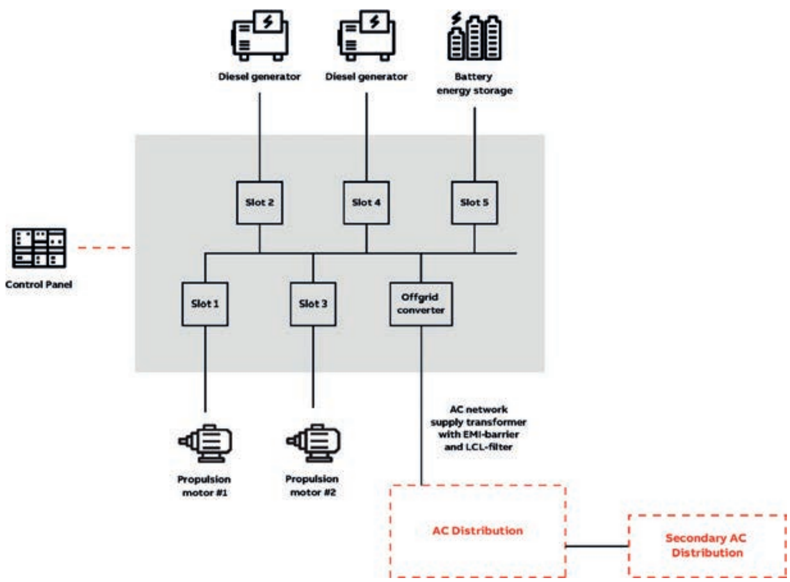
Concept illustration of Onboard Microgrid installed on a ferry

The control system supports up to four selectable operating modes, depending on power sources. Diesel generator sets can be operated utilizing configurable running order and automatic start / stop power limits. In hybrid mode, the system uses energy storage to optimize loading or even out engine load variations.

The control system also provides the possibility for automatic selection of mode, based on defined conditions like battery state of charge, propulsion power and shore power availability. This feature enables e.g. hybrid ferry operations with a minimum need for operator actions.

Mode	Description
Engine	One or more generator sets providing power to the network
Hybrid	Parallel use of generator and battery)
Electric	Power from batteries
AC shore charging	For ship's electrical consumption and battery charging

The propulsion control system supports one propulsion drive in each OMD880LC-unit. This may consist of one or two motors and inverter modules. The propulsion motor may be connected to an azimuthing thruster or shaft line with either direct or geared coupling. The control system



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Increasing power and providing redundancy with simple integration of the control of a second propulsion motor

has built-in support for two control locations. For more complicated control schemes, it can be connected to a separate remote control system.

Supply and control of AC-power generation is also integrated into the OMD880LC. Each drive unit can provide more than 300 kVA 50 / 60 Hz power for standard AC consumers. A dedicated output transformer is used to adapt the voltage level and network type to vessels needs, and to ensure proper EMI filtering.

Where there are two installed units, the system controls supply breakers and bus tie breakers at two voltage levels, e.g. split buses for 440 and 120 VAC.

Onboard Microgrid in a double-ended ferry
The illustration below shows the control system setup of a vessel with two propulsion drives, diesel generators, energy storage systems and shore connection. In a double-ended ferry, the two remote control positions are located in the bridge consoles at either end. Both bridge consoles are equipped with an HMI panel for each drive cabinet, propulsion RPM-levers and push-button/lamp-panels for essential propulsion functions.

The necessary control and monitoring signals for electric power generation, propulsion and AC-network are all handled by the standardized Onboard Microgrid control system, considerably decreasing the amount of project-specific integration work.

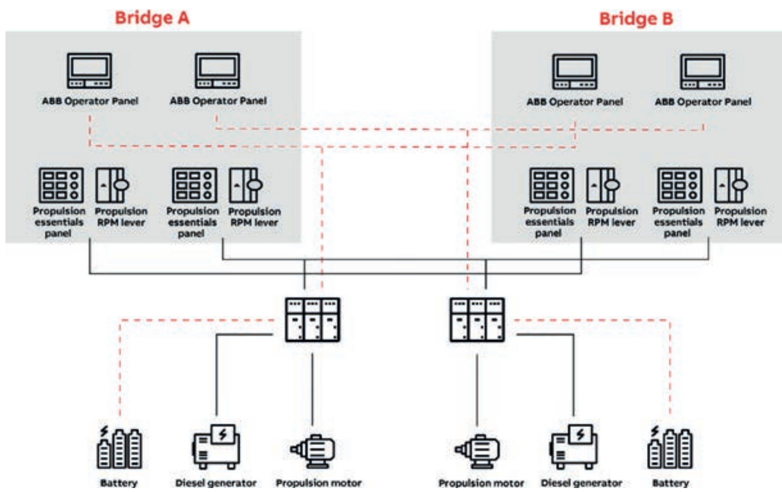
The dimensions of one OMD880LC-unit are 2.1 x 0.8 x 1.3 meters, making it suitable for very low clearage spaces, and the water-cooled cabinet can be placed freely in engine room. In addition to the drive unit itself, space is needed for cooling units, AC-switchboards and transformers for AC network and shore connection. Shore connection systems and battery energy storage solutions are as such not part of Onboard Microgrid, but the system is designed to connect to and control both systems.

Use of DC-bus and electric drives makes it possible to adapt the same hardware in several configurations. In its simplest form, Onboard Microgrid can be used as traditional diesel-electric drive train without energy storage or shore connection systems. In this form, it provides advanced propulsion control and power management functions for a multi-engine electric propulsion plant.

The standard Onboard Microgrid integrated control system supports two-directional operation. The key feature is double-ended mode propulsion control, which sets the power of the forward propeller as a function of aft propeller power. It also considers the direction of the vessel based on control location and allows the operator to de-activate the mode at any time.

Onboard Microgrid with battery energy storage in effect turns a diesel powered ferry into a hybrid vessel, with the possibility of optimizing engine load and operating in zero-emission mode. Energy storage power and energy capacities should be optimized to match engine power and the operational profile of the vessel. One possible use case for a ferry would be zero-emission during harbor stays and maneuvering. Batteries are recharged during the voyage, and the charging power is adjusted to run diesel engines at optimum load. Lower power requirements during maneuvering and time in harbor can be covered by stored battery energy.

Shore connection adds new possibilities for operation of Onboard Microgrid and battery energy storage. In its simplest form this can be a low power supply enabling cold ironing, and possibly slow charging of onboard batteries. It can also be an automated high-power fast charging system for full electric zero-emission operation.



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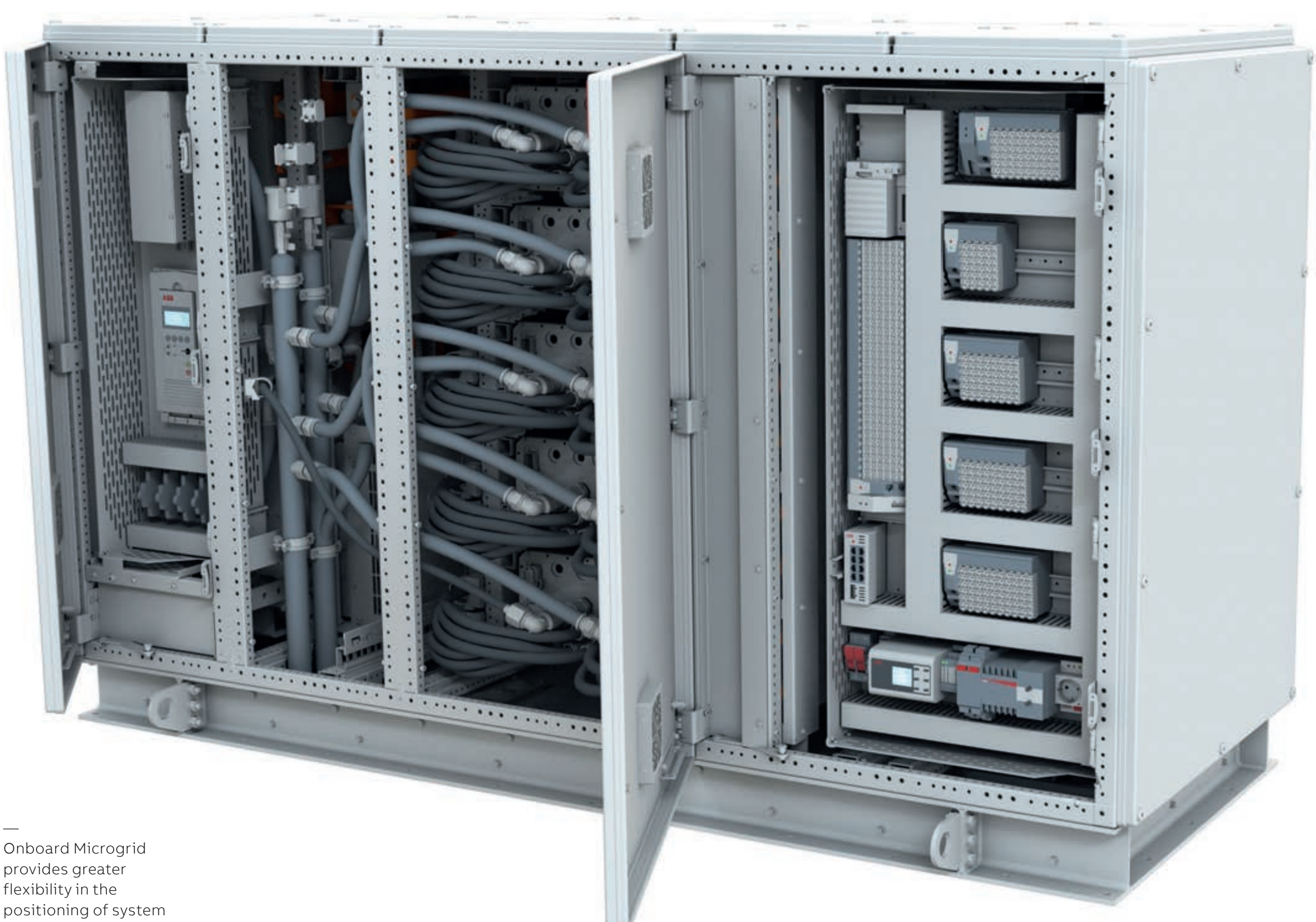
Control system configuration for a double-ended ferry

Integrated system platform
Onboard Microgrid was designed to make shipbuilding and system integration easier. The compact package with DC distribution and all main drives and associated controls within a single unit means savings in engineering and construction. The benefits include a smaller number of components to install, fewer cables to pull and connect, and fewer interfaces to design and test.

Owners also benefit from a truly integrated system. A robust water-cooled DC-system provides high reliability and long lifetime. Use of single frequency converter type and a single control system for all main drives reduces spare part stocks and simplifies troubleshooting. Finally, for the operator, the Onboard Microgrid user interface enables control and monitoring of electric power generation and propulsion systems through a single, intuitive HMI.



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Onboard Microgrid provides greater flexibility in the positioning of system on board

Shaft generation solutions
Taking the next steps to efficiency

This article presents the achievements of ABB shaft generator solutions and the outlook for advanced applications of shaft generators.

VISTA-HAO FENG
CN ES Technology Manager
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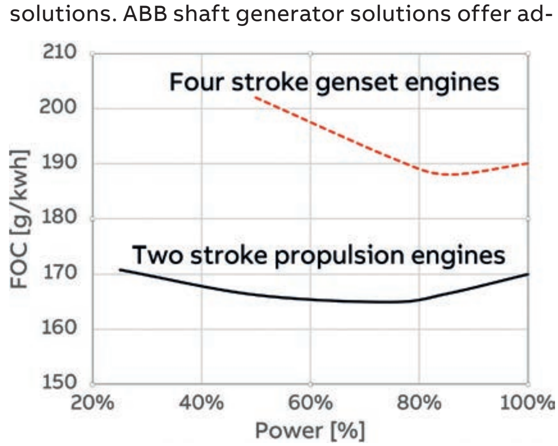
General introduction – shaft generator
In the marine segment, "shaft generator" is defined as the rotation electrical machine that takes power from the main propulsion diesel engine to produce electricity. A shaft generator is not state-of-the-art technology in the marine industry, but it is decades old.

Due to the differences in fuel consumption of the two-stroke low speed propulsion engine and the medium-speed genset four-stroke engine, the shaft generator solution can offer significant fuel savings. It is widely applied in various ship types, especially fishing vessels, Ro-Ro ships, container ships and oil tankers.

ABB Mariine & Ports has been active in the shaft generator segment since the 2010s, focusing on delivering qualified variable speed shaft generator solutions. ABB shaft generator solutions offer advanced performance verified in project after project. The ABB shaft generator solution demonstrates:



- High qualified voltage output: Total voltage harmonic is very low, even to less than 2 percent in some cases
- Powerful short circuit ability: Controllable short circuit magnitude and durations
- Strong dynamic performance: Support the starting up of a motor with high power rating;
- Fast synchronous: Built-in fast synchronous meets variable application
- Harmonic compensation: Provides optional harmonic compensation function to help increase ship grid quality

Besides 'traditional' shaft generator solutions, European owners are incresingly asking for more environmentally friendly and flexible solutions such as battery integrated shaft generator drive systems that require deep insight into various components including the main engine, propeller, shaft generator, auxiliary generator, battery and other consumers. Knowledge of how these components work together and compensate each other to achieve the target set by customer is also required.

Advanced application – shaft generator plus energy storage
With the development of power electronics and energy storage systems, the market is demanding advanced systems able to perform complex functions. The below diagram shows the system in a

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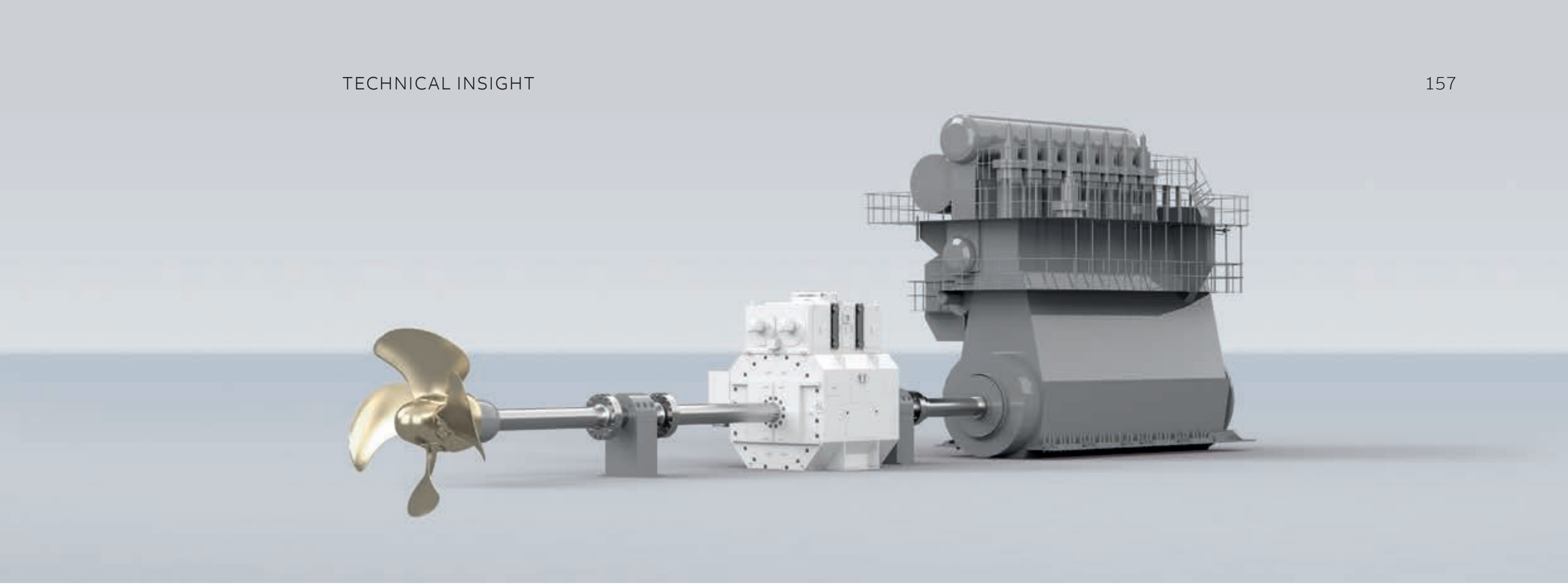

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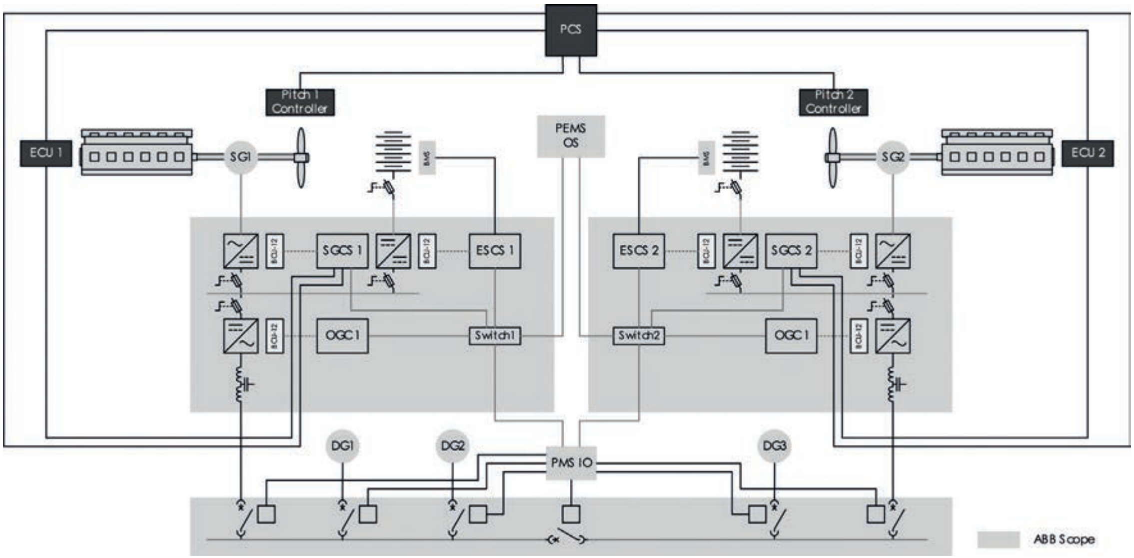
Variable speed
shaft generator

modern Ro-Ro ship, featuring shaft generator together with energy storage, and offering variable operational profiles to enhance system benefits.

In addition to the well known benefits of onboard energy storage systems, like zero-emission in port, there are more functions when a shaft generator works with energy storage:

- Dynamic support for Power Take Off (PTO): Rapid hotel load changes with AC grid can cause mechanical impact at the main propulsion shaft when the shaft generator is working at Power Take Off (PTO) mode, increasing the wear of mechanical components. Energy storage systems enable dynamic support to mitigate mechanical wear and sustain steady shaft generator loads for improved efficiency.
- Dynamic support for main propulsion engine: Propeller characteristics fluctuate when sailing in heavy weather, which may cause the propulsion loads to change dramatically with variations of tide and wind. To ensure that the main engine is working at optimal efficiency, a control system needs to tune pitch accordingly to prevent main engine overload. The consequences of tuning pitch are increased mechanical wear and impact on ship speed. The energy storage system and shaft generator work together to sustain the propeller load variations instead of tuning mechanical propeller pitch.

Future hybrid solutions
Onboard electrical power systems are shifting to hybridization, where variable energy sources co-exist on vessels. Shaft generators offer possibilities to achieve hybrid requirements and help ship-owners to achieve enhanced benefits.



Transforming terminals in the mega-age

The mega-sizing of the shipping industry, with larger ships, hub port strategies, consolidations and new alliances, drives container terminals to transform their operations to stay relevant. Furthermore, the cascading brings the mega-age effect to terminals of all types and sizes, to greenfield and existing facilities alike. This paper discusses three main mega-age drivers for container terminal change and different strategies for implementing transformation.

UNO BRYFORS
Senior Vice President
ABB Ports

Is transformation needed?
In order to answer this question, we have identified three mega-drivers impacting container terminals over the coming years.

1. REMAINING RELEVANT
The mega-age has shifted the focus from building new terminals to re-equipping existing ones to provide the required productivity, high peak capacity and high container storage capacity. Mega-sized cranes are needed for sufficient lifting height, reach and capacity. At the same time, customers expect reduced handling cost per container. However, some of these requirements may be in conflict, or at least inconsistent: improving crane productivity is not so simple since serving large ships is slower than serving smaller ones due to longer trolley/hoist distances and longer ropes. Maintaining high peak capacity may need extra equipment and staff, which can increase the handling cost per container.

2. THE DIGITAL ERA CUSTOMER EXPECTATIONS CHANGE THE GAME
Today, shippers expect guaranteed container delivery times to multiple modalities. Shipping lines have started to diversify their service offerings by seeking premium pricing for fast or guaranteed delivery. This requires predictable productivity and sequenced operations in the terminals involved. Ability to provide real-time information online regarding the status and location of individual containers and correct information for the next actor in the chain are basic requirements in the digitalized world.

3. SAFE AND SUSTAINABLE
Serious shipping accidents have already resulted in enforcement of correct declaration of container weights. The recent significant increase of serious fires onboard ships has highlighted the risks with dangerous cargo, especially on mega-vessels. To limit these risks, terminals and shipping lines will be obliged to accurately track the contents and location of containers onboard. Automated – digitalized terminals are already able to comply with such requirements but new regulations may become a challenge for many manual terminals. Container terminals will be expected to be sustainable and energy efficient members of societies. Emissions, noise and light pollution on today’s levels will not be tolerated. Terminals are also expected to offer a safe and comfortable working environment that promotes team work and collaboration, in a location that is easily accessible for the employees.

The drivers are diverse and, consequently so are the transformation strategies. Automation and

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Transformed to the world leader – GCT Delta Port's intermodal yard now has the highest on-dock rail capacity in the world. The widespan cranes are equipped with ABB's automation and remote supervision system.

digitalization will naturally play a critical role, but there is more to consider.

Transformation at the terminal level

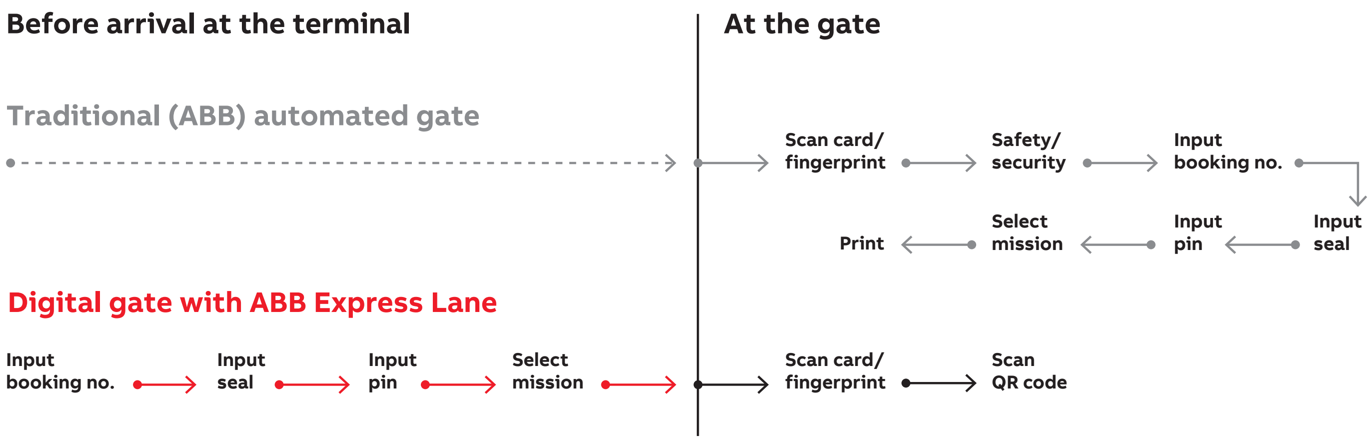
A holistic analysis of a terminal's existing operations provides a basis for reconfiguring operations focusing on the weakest link (or links). The weakest link is not necessarily a big-ticket item and yet addressing it often results in significant increase in a terminal's capacity. The weakest link can often be found in manual processes (e.g. at the gate/handoffs), poorly integrated/sized yard or on-dock rail operation, lack of competence, poorly organized exception handling, or inadequate utilization of automation and logistic systems.

Terminal-level transformation can be achieved by deploying equipment in a flexible way, supported by automation. Scheduling and prioritization of container moves, vehicles and cranes based on real-time information can save seconds and minutes at every move resulting in significant total productivity gains.

Optimizing the net production time is the fastest and cheapest way of improving productivity. This is enabled by crane and process automation. Deploying remote operation on all types of cranes eliminates interruptions caused by breaks and moving staff to, from and between cranes, as well as enables the use of higher crane motion speeds and accelerations. Remote operation provides an ergonomic working environment for the equipment operators and enables unified management of exception handling for cranes, gate and vehicle identification, contributing to maximized net production time.

Digitalization is not only about big data and clouds; it also brings significant opportunities for transformation of operational processes. The numerous systems already being used in container terminals constantly collect data about events, operational exceptions and debugging information. What the systems themselves need to 'know', they already know; it is just that they have not been able to pass on all of the information to the staff

Transaction time at the gate down by up to 50 percent



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Digital gate – ABB's Express Lane allows most of the actions to be made before arrival at the gate via mobile app / web interface.

operating the terminals. Visualization of that data enables monitoring of the entire logistical flow from individual machines and immediate actions can be taken as necessary. It also provides means for analyzing and evaluating the processes execution, studying equipment performance and understanding equipment health, enabling terminals to achieve continuous operational improvements.

Transformation at the quay
At the quay the transformation to mega-age capabilities can be based on the equipment itself or on the re-engineering of processes. Based on the needs and the goal of the transformation, there are several options that can be considered:

- Upgrade the existing STS cranes to increase lifting height/outreach. When considering this option, it is important to analyze if the structurally upgraded cranes will meet functional requirements in the long run, and whether components (e.g. electrical systems/equipment) should be replaced during the upgrade, considering the expected remaining lifetime of the crane.

- Automated or manual STS cranes. The taller cranes of the mega-age pose a challenge even for an experienced and skilled crane operator. Automation system supports the operators and makes every operator a good operator which makes the production predictable.

- Digitalization. By fully digitalizing the information exchange between (remote) crane operator, checker and deck-man, i.e. within the team involved in the operation of STS cranes, the entire quay operation can be digitalized, and checkers become remote checkers overseeing several cranes from the control room. Digitalization brings the remote operation to the next level, supporting continuous operation by solving logistic exceptions without impacting the crane cycles.

Transforming on-dock rail operations
For many terminals, transformation of on-dock rail operations offers great opportunities to increase terminal capacity. Introduction of automatic intermodal yard gantry cranes (IYCs) gives several significant benefits. The automated motion sequence, including landing on chassis and rail cars supported by remote operation, allows the full capacity to be utilized continuously. Additionally, the IYCs shorten the transport distances in the yard and result in better utilization of yard space. Higher on-dock rail capacity means less road vehicles, which improves the sustainability of the terminal's operation but also results in a more predictable and efficient operation.

GCT Delta Port in Vancouver recently completed the re-configuration of their intermodal yard resulting in the world's highest on-dock rail capacity and an efficient layout that optimizes the terminal's traffic flow. The terminal remained fully operational throughout the project in which smaller manual RMGs were replaced with eight automated and remotely supervised widespan IYCs.

Transforming yard operations
The mega-age yard needs to be equipped to provide a cost-efficient service for both waterside and landside operations. In many terminals around the world, automated cantilever stacking cranes (ARMGs) have proven to be an efficient solution for obtaining substantially higher yard capacity and productivity. Cantilever stacking cranes can handle wider blocks, yielding up to 20 percent more storage capacity within a given space/stacking height compared to yards with RTG operation.

Higher motion speeds, fast automatic positioning/landing and better scheduling capabilities make automatic-unmanned cantilever stacking cranes more productive than RTGs which means less machines. They allow flexible capacity deployment within and between blocks supporting the landside and waterside operations, which increases peak and average production capacity as all cranes can be used efficiently.

With automatic single or double cantilever cranes the pick-up/landing on the internal chassis can be fully automated, and only limited supervision is needed for handling road trucks. With one operator overseeing many cranes, the overall efficiency of the operation becomes very high.

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Motion control and automation systems of ARMGs log a huge amount of data. Via digitalization, everything that these systems already knew but couldn't tell us can now be visualized and analyzed. Operational data (KPIs) and all data about container moves, orders, motions, interactions and the equipment itself, is stored. Data about an individual crane or the entire crane fleet is visualized in 2D/3D presentations.

A typical yard transformation project today is an extension or re-equipment of an existing yard. This can include transforming manually operated RMGs into automated and remotely supervised cranes. For instance, the FICT terminal in Tianjin, China, recently upgraded and automated 31 RMGs to increase the terminal's capacity by improving the efficiency of the yard operation.

Transformation at the gate
Automated gate operation has significantly reduced the gate transaction time compared to manual operations by eliminating costly and inefficient manual processes and by enabling centralized exception handling.

However, it is possible to reduce gate transaction times by up to 50 percent compared to traditional automated gate by deploying digital gate. This represents a big saving in terms of time and cost for terminal operators, especially those serving mega vessel calls.

A digital gate is based on pre-arrival check-in (comparable to an on-line check-in for air travelers), which ensures that booking details are correct before the arrival at the gate. With pre-arrival check-in completed via a mobile app (by the truck driver him/herself) or web interface (by the dispatcher), the driver only needs to handle the identification if required (finger print or card scan) and scan the QR code from his mobile app and he/she is cleared to complete the mission.

Conclusion
Transformation will be needed in the vast majority of terminals with varying handling concepts and needs. It is essential when selecting the strategy to avoid short term sub-optimization, and instead to specify for the future.

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Increasing terminal capacity by 10 percent
A case study in yard transformation

This paper examines the way Tianjin Five Continents International Container Terminal Co. Ltd. (FICT) in China resolved the 'mega-age' yard challenge by modernizing and automating its existing manual RMGs. The case study explains the solution and improvements in KPIs achieved by improving the efficiency of yard operations.

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As discussed in earlier papers written by ABB, we inhabit the 'mega-age' of megaships and consolidated shipping lines. It is an era which has forced the need to re-equip existing terminals and improve efficiency and productivity into the spotlight. To avoid becoming a bottleneck, the yard of today needs to be equipped with solutions that can support the required increase in capacity and productivity while retaining cost-efficient service to both waterside and landside operations.

About FICT

FICT, which is part of Tianjin Port Container Terminal Co., Ltd., is located in the Port of Tianjin. With 500 international port calls per month and total yearly volumes of 16 million TEU, Tianjin is the tenth busiest container port in the world and the largest in Northern China. The port is also the main maritime gateway to Beijing and serves as a link between the Northeast Asia, Central Asia and the Middle East.

The terminal was built in 2003 and was originally designed for annual throughput of 1.5 million TEU, which has become insufficient in the mega-age. In 2018 the terminal's actual volume clearly exceeded the design capacity and reached 2.57MTEU.

The terminal's perpendicular yard is equipped with 31 RMGs which were originally manually operated. It has capacity to store containers corresponding 32,000 TEU. The RMGs at FICT are not typical cantilever type cranes. They are specifically designed for this terminal and have two vehicle lanes within the crane portal on one side. This means that both internal and external chassis are served in the same lane whereas the second lane is used to allow the chassis to pass the vehicles in the service lane. In addition, some of the cranes have a rope tower, while some have reeving that resembles a ship-to-shore (STS) crane.

The bottleneck

FICT identified the need to increase the efficiency of the yard early on, with congestion resulting in long truck turnaround times and the yard filled up with containers stacked 5-6 high. Work during the night showed low efficiency and there was a huge imbalance in the workload between the cranes and therefore between crane drivers. The difficulty of recruiting crane drivers and increasing labor costs added to the problem, further restraining the growth in terminal volumes.

The arrival of mega ships, with a requirement to handle 7,000 containers in 30 hours, created frequent peaks in production and placed new demands on equipment performance requirements. In effect, the yard had become a bottleneck hampering the future development of the entire

The yard transformation in numbers

- 10 percent increase in the terminal's production capacity
- 35 percent increase in equipment utilization
- 20 percent increase in container handling capacity at the yard
- Monthly average moves/hour at the yard: 30
- Number of moves/hour at the quay up by 5 moves
- Truck turnaround time down from 51 minutes to 18 minutes
- The yard was fully operational throughout the project
- The entire project was completed in 13 months

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The 31 manual RMGs were modernized and automated to increase the yard efficiency.

terminal; therefore, the yard equipment and processes needed a total make over to support larger container throughput in the terminal.

Re-equipping and automating the yard
In parallel with the capacity limit, after 15 years in operation the electrical systems installed in the cranes had reached the stage where refurbishment was needed. These circumstances created an opportunity for the terminal to raise the performance of its yard operations to a new level at the same time as it upgraded its crane control systems. Thus, a decision was taken to automate the yard operations, with the target of increasing the yard's production capacity while also improving cost-efficiency.

In the modernization project that was executed by ABB, the old crane electrical and control systems were fully retrofitted. The new systems were fitted in new innovative, containerized e-houses that were delivered pre-assembled to the terminal to enable faster project execution on site.

Major part of the process on the yard was automated. Pick-up and set-down of containers on internal terminal chassis are now fully automatic, since there is no twistlock handling and the automation system is equipped with a truck supervision function that ensures that the vehicle is in the right position and does not move during the set-down of the container.

As noted, both external and internal chassis are served in the same lane in a single-side two-lane operation at FICT. Therefore, ABB's 3D sensor based antilift system is used to scan the vehicle as part of the vehicle guidance process and verifies the vehicle type to eliminate safety risks caused by interference in RFID signals caused by vehicles passing by in the adjacent lane. As the cranes were automated, the operators also moved to a new control room from where each operator supervises six cranes. The interface between TOS and cranes was also upgraded to support the automated process and work order handling.

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Crane operators' new working environment at FICT

Re-equipping 31 RMGs in the yard while keeping the terminal fully operational during the project was a key requirement and careful planning was necessary. A 40-stage reconstruction plan was created in collaboration between nine departments affected at FICT. A close collaboration was also established between ABB as crane control and automation system supplier and TOS supplier Navis. The planning resulted in a rolling weekly construction progress program that made sure that enough equipment remained in operation while a part of the crane fleet was under refurbishment and modernization.

Creating a flow
The introduction of an automated process requires the creation of a flow – a predefined sequence of events with triggers that initiate the next step in the flow. In the operation of a perpendicular yard the relevant triggers are the vehicle positions.

At FICT vehicles are monitored in real time using a RFID within the terminal's premises, with RFID antennas installed at the terminal gate, by the terminal's internal roads and on the yard cranes. The instructions and list of work orders issued by the TOS are processed through an equipment control system (ECS) that takes decisions on the sequence based on defined criteria such as time, priority or energy consumption.

The vehicles get instructions and drive to a specified block and bay close to the crane that will perform the pick-up or set down of the container. When a vehicle approaches the block, the ECS dispatches the work order to the crane based on information about the vehicle location. In the case of external trucks, the TOS schedules a work order based on the truck 'checking-in' at the terminal gate and on the location of the target block in the yard. Ideally, the crane is in the right position ready to perform the pick-up/landing when the vehicle arrives to minimize the waiting time.

The truck driver can verify that he has arrived at the right position from a screen attached to the crane which displays the registration plate. The crane also verifies that the vehicle to be handled matches with the work order with help of RFID. In case the vehicle does not arrive at the crane within the estimated time frame, the crane requests remote operator assistance.

Results
The transformation project reached all of the targets set. Thanks to careful planning and collaboration, the terminal remained fully operational throughout the project's execution, and the whole project of modernizing 31 RMGs was completed in 13 months.

The KPIs show that automating the RMGs resolved the yard challenge. Yard congestion has disappeared as the entire crane fleet is now used more efficiently, with cranes consistently achieving 30 container moves per hour day and night. The equipment utilization ratio has increased by 35 percent. The higher and consistent production has also increased the speed of yard turnover, which in turn has resulted in fewer containers stored in the yard significantly reducing the need to stack 5-6 high.

The container handling capacity at the yard has already increased by over 20 percent and is expected to increase even further. The turnaround time for road chassis has gone down from 51 minutes to 18 minutes.

On the quay side the ship berthing time has reduced by nearly 20 percent and the STS cranes can now perform five more moves per hour than before. Measured at the terminal level, the yard transformation has increased the terminal's overall production capacity by 10 percent, which allows FICT to serve more vessels than before and provide more efficient and reliable service to its customers both on the water and landside.

It was also remarkable to see that the terminal's capacity increased already during the project execution itself. We can conclude that the transformation project was successful and delivered to the requirements and expectations of FICT. The FICT case also verifies that transforming an existing terminal and eliminating the bottleneck allows an existing terminal to increase its capacity and thus remain relevant in the 'mega-age'.

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The Bridge Zero concept and the lookout requirements

Lookout requirements for Bridge Zero (B0) – a conditionally and periodically unattended bridge – can be met by technology.

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When assessing the possibilities to define a machine-based lookout for use in ships in international commercial traffic, it quickly becomes apparent that the current legal system needs some adjustment. The provisions in SOLAS, STCW 2010 and COLREG are very descriptive with the weight of definitions in matters such as the construction of the bridge, the eyesight and hearing of an able seaman or rating of the watch. In a goal-based system, we would prefer a functional description with the minimum levels of information input defined.

Originally the navigation watch consisted of the officer of the watch, the lookout and the helmsman. If the situation demanded it, the watch could be extended with the master, a pilot and an additional lookout. In this paper the task is to evaluate the possibilities and challenges in substituting the function of the lookout with a technology-based system.

In general, the practice of automating functionalities in the marine industry has a requirement to achieve "equal or better" level of safety with the automated system in comparison to the manual system. Therefore, the main challenge is to define the current level of safety. Human performance is defined rather vaguely and depends significantly on the individual, state of health, alertness, time of day, environmental conditions, etc. This makes defining the current performance level not at all straightforward. In the current regulatory system, there are no quantitative threshold values which would define the minimum performance level. In order to define the requirements for the technology that would achieve "the same or equal" performance as the human lookout, such definitions are needed.

This paper discusses the performance of the lookout function from the available sensory input data and associated fundamental limitations presented by the human lookout, as well as indicates that equal level can be achieved by means of technology. In addition, the focus is not on the audible sensory input, as it has been already accepted since the introduction of closed bridges that the audible signals can be provided by the so-called 'elephant ears' – a sound perception device [1]. The main challenge from the regulatory perspective today is in substituting the human eyesight and decision making based on the sensory input.

The paper mainly focuses on the open sea navigation tasks with no land in sight and where other vessels are generally far away. The objective is to propose that the lookout requirements related to the B0 situation – a conditionally and periodically unmanned bridge – can be achieved by the means of technology.

Tasks and requirements of the lookout
The purpose of the lookout is simple. So simple, in fact, that it is sometimes overlooked. As the purpose of the navigation rules is to prevent collisions, it follows that the purpose of the lookout

is to collect the information required to avoid collisions. This fundamental reason for maintaining a proper lookout is something to keep in mind. The function of the lookout can basically be divided into two specific areas: the safety of the own vessel and the safety of everyone else in the vicinity.

According to the current regulatory system, the tools of the lookout are sight, hearing, and 'all available means'. It is also stated that the lookout shall have the mental capacity to interpret the information available through the means at hand. It also goes without saying that the function has no meaning unless the information can be relayed to the officer of the watch in an orderly fashion with the best possible accuracy.

STCW 2010 Medical requirements for duty on deck:
- Vision (appendix A), hearing (appendix B) and physical capabilities (appendix C)
- Impairment from the use of medication (appendix D)
- Presence or recent history of an illness or condition (appendix E)

The functionality of the lookout can and should be described as assisting the officer of the watch to obtain the best possible situational awareness with regards to the operating environment. The description of the function of a lookout is as follows: "Maintaining a continuous state of vigilance by sight and hearing as well as by all other available means, with regard to any significant change in the operating environment" at all times in all weather conditions both day and night. 'Significant' in this context refers to the relative quality of the information input to the officer of the watch and will be one of the key topics. This part of the code is hard to translate into an algorithm but at the same time may be the most important part.

"Fully appraising the situation and the risk of collision, stranding and other dangers to navigation" is key to the safety of the own vessel and rather well understood and rather straight forward.

"Detecting ships or aircraft in distress, shipwrecked persons, wrecks, debris and other hazards to safe navigation" describes both the safety of the own vessel and the safety of others. This has also been one of the most discussed parts in the discussion of MASS. How do we ensure that any party in distress in high seas will receive the best possible chance of being detected and recovered? The requirement will need to encompass a degree of image and pattern recognition.

Today we can already periodically and conditionally merge the functions on the navigational watch to only the officer of the watch performing all the duties described as the functions for safe navigation. This has only been possible with the evolution of supporting technologies. The requirement of hearing, as mentioned earlier, has already been substituted with technology approved by the International Maritime Organization.

It is to be noted that the helmsman was always to act only as the helmsman which means he or she could not be tasked with the function of lookout. Later with the development of navigational aids such as the autopilot the helmsman could be dropped from the muster list provided that the vessel is equipped with a functional and approved autopilot.

One specific task that should be included in the future definitions and possible rule change would be the detection and reaction to a ‘man overboard’ situation.

Current performance of human lookout – sensory input for decision making

Modern SOLAS ships have mandatory navigational equipment for assisting in determining the position, heading and detecting the relevant obstacles in the surroundings. In practice, the vessels typically have radar, gyrocompass, ECDIS, GNSS-based positioning system and an AIS receiver. In addition to these devices, the lookout uses his or her own senses, mainly eyes and ears to perceive the surroundings. If hearing is disregarded due to the already existing acceptance of the electronic hearing devices, the main sensory input for targets that are far away, in addition to the above-mentioned navigational equipment is the human vision.

Human eyesight performance

Human eyesight performance depends on the eye health, the visual acuity (clarity of the vision), light and obstacles (such as fog) in the line of sight, as well as the target the human is looking at. Defining the current level of eyesight performance of the human lookout from the physiological perspective is not unambiguous and is therefore not addressed in detail in this paper. Instead, this paper adopts a common definition of the human eyesight angular resolution, which is approximately 1 arcminute [2]. In practice this means that human can distinguish an object from a point or another object if the object extends 1 arcminute (0,0167 deg), when focused. The reason to choose this criterion is that in the marine environment, the background is always textured and dynamic due to the sea surface and light conditions. Therefore, the target smaller than 1 arcminute criterion will most likely not be distinguishable from the textured background. This means that the further the object is, the larger it needs to be in order to be detectable by a human. The practical aspect of the human eyesight resolution definition adopted in this paper is illustrated in Figure 1, where the human eyesight resolution is denoted by:

$$\alpha_{res,h} \approx 1\ arcminute \approx 0{,}0167°.$$

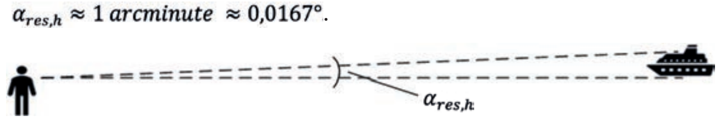

Figure 1: Illustration of the human eyesight resolution

Fundamental boundary conditions

From the perspective of physics, there are two main aspects which fundamentally limit the ability of a human lookout to detect targets from the bridge. Namely, the curvature of the Earth and the meteorological visibility. In perfect visibility conditions, the maximum range of the human vision performance to detect targets is limited by the curvature of the Earth, provided that the object is large enough to be detectable by a human. In order to determine quantitative boundary values for the performance of the human lookout, very conservative fundamental limitations can be set by the visibility and the curvature of the Earth.

Limitation due to the curvature of the Earth

The curvature of the Earth limits the visibility of the targets in the horizon at open sea. The maximum distance that an observer with a height h_O can detect a target with a height h_T in a horizon can be approximated by:

$$D_{max} \approx 3{,}57 \cdot \left(\sqrt{h_O} + \sqrt{h_T}\right)\ km.$$

As an example, consider an observer at height of h_O = 30 m and an object of height of h_T = 30 m. In this setup, the distance the object disappears below the horizon is approximately D_{max} = 39,1 km. Target of the same height further than this will disappear below the horizon due to the curvature of the Earth.

Combining the curvature of Earth limitation to human eyesight resolution

Combining the curvature of Earth limitation with the minimum angular resolution of human eyesight, it is possible to calculate the practical maximum range of a target above the horizon that is detectable by a human. This can be achieved by matching the maximum distance and the resolution. The height of the object $h_{T,r}$ at distance $D_{max,h}$ matching the human eyesight resolution $\alpha_{res,h}$ can approximated by:

$$h_{T,r} \approx \alpha_{res,h} \cdot D_{max,h}.$$

Combined with the distance approximation due to the curvature of Earth so that the object is $h_{T,r}$ above the horizon, one obtains:

$$\begin{cases} D_{max,h} \approx 3{,}57 \cdot \left(\sqrt{h_O} + \sqrt{h_T - h_{T,r}}\right) \\ h_{T,r} \approx \alpha_{res,h} \cdot D_{max,h} \\ 0 \le h_{T,r} \le h_T \\ D_{max,h} \ge 3{,}57 \cdot \sqrt{h_O} \end{cases},$$

Solving $D_{max,h}$ from the equation gives the approximation of the range a human can detect.

As an example, considering an observer with h_O = 30 m, combined with the human eyesight resolution, a h_T = 30 m high object becomes distinguishable for a human when the object is approximately at $D_{max,h}$ = 35,4 km distance. In this distance the object is $h_{T,r}$ = 10,4 m above the horizon, which is approximately 1 arcminute in angular resolution from the observer. The principle of the calculations is illustrated in Figure 2.

Limitation due to the visibility

The visibility in the lookout context defines the distance by which an object or light can be clearly discovered. The visibility can be decreased by fog, haze, rain, etc. disturbance which absorbs, scatters or blocks the visible light wavelengths and therefore decreases the visible range. The definition of visibility as a range is not unambiguous as it depends on the target properties, light conditions, etc. Therefore, this paper assumes that if the target is further away than the visibility range, a human lookout cannot detect it. On the other hand, if the target is closer than the visibility range, the human lookout can determine it. Therefore, this paper assumes that the visibility sets the maximum range that the human lookout can detect an object relevant for performing the lookout function.

Implications and minimum requirements for technology – minimum sensory input for machine-based lookout

As discussed above, the sensory input for the officer of the watch are the SOLAS navigational aid equipment as well as the human eyes of the lookout. As the SOLAS navigational aid equipment is already digital, the main challenge is to define the technological requirements to achieve "as good or better" detection performance by visual means. The most advanced, yet commercially feasible technology to achieve the visual perception is camera technology, equipped with computer vision. In the following, the camera technology requirements are analyzed based on the chosen resolution criterion and the limitations set by fundamental boundary conditions, mainly focusing on the good visibility situation where the main boundary condition is the curvature of the Earth.

The human lookout performs the sensor fusion, that is, combining the sensory input from each modality (visual, radar, charts, etc.) to determine the overall assessment of the situation manually. Given the resolution criterion and the boundary conditions as proposed in this paper, in order to achieve the performance comparable to human capabilities, the performance of the camera system should be able to detect targets using computer vision with 1 arcminute resolution up to the maximum distance limited by the curvature of Earth in good visibility conditions. In addition, the system needs to be able to detect targets up to the distance limited by the meteorological visibility.

If the above can be demonstrated, the minimum level of a lookout – that is, detecting the targets – is shown to be 'as good or better' than human.

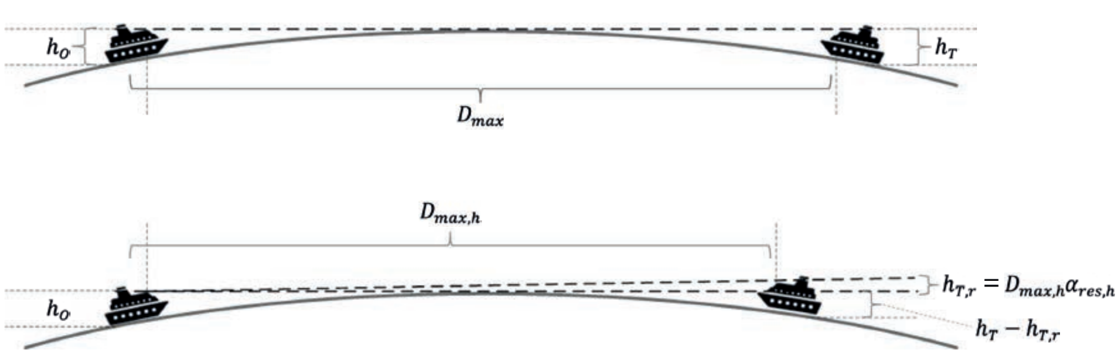

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Figure 2: Illustration of the limitation due to the curvature of Earth (top) and the decreased maximum range due to the human eyesight resolution (bottom).

Comparison of camera technology and human performance

In camera-based surveillance and monitoring, there are standard, accepted ways to estimate the maximum range a camera system with given specifications can monitor, detect, observe, recognize, identify an object. The IEC standard 'IEC 62676-4 Video surveillance systems for use in security applications – Part 4: Application guidelines' defines the requirements for each of the surveillance task. Detection is defined as an ability to detect a presence of an object. This is essentially the primary task of the lookout function, that is, detection the presence of targets which are 'something else than water'. With the digital camera technology, the different tasks such as detection, recognition and identification are determined by the number of pixels. The minimum projected dimension of an object needs to be represented in the picture in order for it to be able to detect, recognize or identify the object.

The threshold for detecting a human presence (0,5 m x 1,7 m) is 25 px/m, where px refers to number of pixels. In practice, this means that the width of a human projection (0,5 m as a standard) needs to be represented by 12,5 pixels. Assuming that each dimension needs to be represented by 12,5 pixels in the picture, one can calculate the angular resolution and therefore the maximum range the camera could detect an object, possibly limited by curvature of Earth. The calculations can be done by modifying the formulae described above for human performance.

As an example, consider a Full HD Pan-Tilt-Zoom (PTZ) camera with resolution of 1920 x 1080 and zoom so that the minimum horizontal field of view is 2,3°, installed at 10 m height. The standard DRI detection criteria and the associated detection distance, taking into account the Earth curvature can be calculated for various marine-relevant targets as illustrated in Table 1. The detection distance with human eyesight is also estimated using the previously described formulas.

As Table 1 shows, the example camera setup can achieve equal or better resolution compared to the human eye. Obviously, there are several technical solutions which achieve the same through different configurations of camera and optical technologies. The purpose of the table is to illustrate that in good visibility conditions the camera technology can meet the criteria of human eyesight resolution.

Note that in practice both the human eyesight performance, as well as the camera performance is affected by several factors, including air quality, humidity, vapor, light conditions, contrast, color and reflectivity of the object, etc. Camera performance is also affected by clarify of the lens, the focus, mechanical vibration, etc. aspects not considered in this paper.

Experimental results and illustrations – experimental setup

In order to test the theoretical calculations, an experiment was performed. The experimental setup included ABB Ability™ Marine Pilot Vision situational awareness system installation with a full HD PTZ-camera and 30x optical zoom. The horizontal field-of-view of the camera with maximum zoom settings was 2,3°. The camera was

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Table 1: Comparison of estimated detection distance for various marine-relevant targets in perfect visibility conditions based on 12,5 px/minimum dimension of the object (full HD PTZ camera with 2,3° horizontal field-of-view installed at 10 m height) combined with Earth curvature limitation, and human eyesight resolution combined with Earth curvature limitation. Note that the calculations are based only on the height of the object, as that is typically the limiting dimension.

	Length (m)	Height (m)	Beam (m)	Detection distance – camera (km)	Detection distance – human eye when focused (km)
Small boat	4,7	1,0	1,5	3,8	3,4
Small pleasure craft	7,0	1,5	2,6	5,7	5,2
Medium pleasure craft	10,2	3,0	3,5	11,4	10,3
Small passenger ferry	33,0	6,0	8,0	16,1	15,6
Bunkering vessel	87,8	26,6	13,4	27,1	26,8
Ropax vessel	136,1	30,0	24,2	28,3	28,0
Medium range tanker	205,7	30,5	34,3	28,4	28,1
Aframax	246,9	33,5	41,1	29,4	29,2
Suezmax	289,6	45,7	48,3	33,0	32,8
VLCC	378,0	61,0	63,0	36,9	36,6

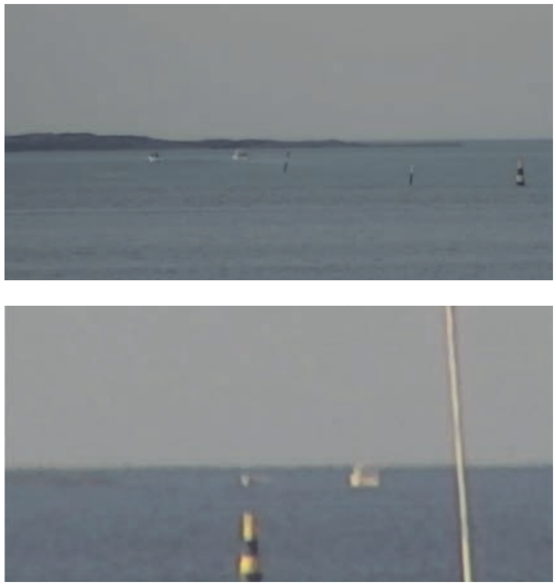

Figure 3: Two boats at 6,.8 km (leftmost the “Small pleasure craft” and rightmost the “Medium pleasure craft”). Picture below – the same boats at approximately 9,6 km. Note that the zoom settings of the pictures are different.

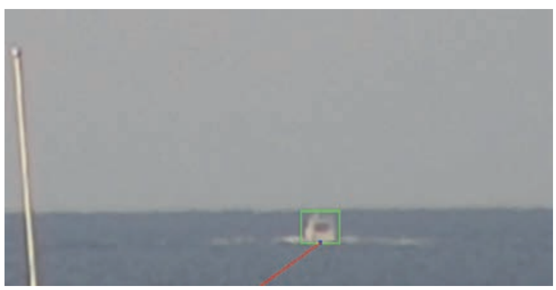

Figure 4: Deep neural network based detection of the ‘Medium pleasure craft’ at around 9,6 km

installed at the height of 10 m. The vessel where the camera was mounted was stationary during the experiment.

Two pleasure crafts with dimensions equal to the ‘Small pleasure craft’ and ‘Medium pleasure craft’ described in Table 1 were used as detected targets. The boats were navigated to a specific distance from the vessel where the camera was mounted. The weather was clear during the experiment with 4 m/s wind from north east. The air pressure was 1019 hPA and the visibility was good. The time of day during the experiment was 04:00 am to 06:00 am. The test was done in the Helsinki estuary.

According to the results, as illustrated in Figure 3, one could detect the boats with a camera even further than the standard detection criterion indicates. With the mentioned equipment, vessel size and the installation height of the camera, the ‘Small pleasure craft’ should be detected at around 5,7 km, whereas the boat is still detectable at 6,8 km. The ‘Medium pleasure craft’ could be detected clearly still at 9,6 km. Figure 4 presents the detection result of a deep neural network based image processing algorithm trained to detect vessels from background. As an example in this picture, the "Medium pleasure craft" is detectable at 9,6 km.

From detection to decision

The human lookout needs to manually process, remember and track the targets detected visually. The targets detected by AIS and ARPA radar are tracked by the machine. When the association of the information is done by a human, it is likely that if the situation persists, the human can forget the existence of some targets, which can lead to a wrong assessment of the situation. In machine-based lookout, monitoring the surroundings is continuous and relentless. The system keeps track of the targets, monitors and predicts their movements and does not forget information in a way a human might do. Moreover, the system is neither affected by the human mental state nor the limited capability of a human to process information and detect changes.

Beyond human performance

As discussed above, the minimum level for machine-based lookout performance is to demonstrate that the visual acuity in different boundary conditions match human performance. Modern perception technology allows to achieve performance beyond the human perception capabilities. For example, infrared (IR) camera technology enables the detection of targets in decreased visibility conditions, whereas the human eye cannot see even when using binoculars. Short wave infrared (SWIR) cameras enable detection of other vessels even through fog and long wave infrared (LWIR) cameras enable detection of other vessels, debris and floating obstacles even at pitch black conditions and decreased visibility conditions.

It is also important to recognize that the high-end technology that helps achieve the perception levels beyond the human performance increases the cost of the system, and therefore the additional benefit of achieving the ‘better than human’ level needs to be considered from practical and financial aspects as well.

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Tube-based model predictive control for dynamic positioning of marine vessels

This paper focuses on the design of a robust model predictive control (MPC) law for dynamic positioning (DP) of marine vessels in the presence of actuator saturation and environmental disturbances.

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The proposed solution is a tube-based MPC ensuring robustness and constraint fulfillment. Formulation of the tube-based MPC relies on a sufficient robust invariant set condition, along with a linear matrix inequality (LMI) synthesis procedure, and an efficient analytical Pontryagin set difference computation. Simulation results show the effectiveness and satisfactory behavior of the proposed controller.

Introduction

Autonomous marine vessels have been a subject of substantial recent interest in both the marine industry and the academic control community. On the business side, there is a significant potential to reduce marine accidents and costs connected to human mistakes (Apostol-Mates and Barbu (2016)) whereas on the academic side, the dynamic characteristics of marine vessels result in control problems that challenge the state-of-the-art, see, for example, (Fossen and Strand (2001); Johansen et al. (2004); Do and Pan (2009); Caharija et al. (2014)) and references therein.

Among the broad range of control challenges for autonomous marine vessels, dynamic positioning (DP) is a task of particular interest. Traditionally, a marine vessel is said to have DP capability if it is able to automatically maintain a predetermined position and heading angle using active thrusters. The development of DP systems for marine vessels have been widely studied in the literature, using several different control strategies (Pettersen and Fossen (2000); Loria et al. (2000); Sørensen (2011)). Nonlinear control strategies are among the most popular ones, since ship dynamics can be characterized by nonlinear differential equations (Fossen (2011)). The mainstream nonlinear techniques for DP include the Lyapunov-based backstepping (Fossen and Grovlen (1998)) and sliding mode control (Tannuri et al. (2010)).

An important aspect usually neglected on DP control design is to explicitly account for physical constraints on forces and torques generated by thrusters. In general, either such constraints are completely neglected, or the controller is specially tuned so that they are not violated under desired conditions. One of the few techniques in the literature which is capable of handling constraints is model predictive control. MPC is by now an established multivariate control technique for constrained linear systems (Rawlings and Mayne (2009)). In addition, the basic technique can be extended to deal with nonlinear, hybrid, and switched systems (Allgöwer and Zheng (2012)). The viability of using MPC for DP was established in Veksler et al. (2016), who presented compelling advantages over state-of-the-art techniques. To the best of our knowledge, there are no papers which study the DP problem under environmental

disturbances, such as wave, wind and ocean currents, while explicitly enforcing constraints.

In order to address this problem, we develop a tube-based MPC for dynamic positioning of marine vessels. In particular, the controller consists of two terms: a nominal control input, which is the outcome of a finite horizon optimal control problem and is computed offline; and an additive state feedback control law, which is designed offline and implemented online (along with the nominal control input) for vessel control, guaranteeing that the real trajectory of the closed-loop system will belong to a tube centered along the nominal trajectory. We also present an efficient approach for the Pontryagin set difference calculation required for control design. In order to test the performance of the controller, we perform a numerical simulation on a nonlinear vessel model subject to external disturbances.

Problem formulation

Notation: We let $\mathbb{R}$ and $\mathbb{N}$ denote the set of real numbers and natural numbers, respectively. A polyhedron is the (convex) intersection of a finite number of open and/or closed half-spaces and a polytope is a closed and bounded polyhedron. Given two sets $X, Y \subseteq \mathbb{R}^n$, the Minkowski sum is defined by

$$X \oplus Y = \{x + y \mid x \in X, y \in Y\},$$

and the Pontryagin set difference is

$$X \ominus Y = \{x \mid x \oplus Y \subseteq X\}.$$

We describe henceforth in this section vessel's kinematics and dynamics equations and formulate the DP problem.

Ship model

Kinematic equations of a 3-DOF marine vessel model, relating its body-fixed frame and its inertial frame velocities, can be written as (Fossen (2011)):

$$\dot{\eta} = R(\psi)\nu. \tag{1}$$

Here, $\eta = [x,\ y,\ \psi]^\top$ denotes the position and orientation of the vessel, where x and y are the ship's geometric center of gravity and ψ is the heading angle, all of them written with respect to the inertial frame. The vector $\nu = [u,\ v,\ r]^\top$ denotes the velocity of the vessel, where u and v are the surge and sway velocities, and r is the yaw velocity, all of them written with respect to the body-fixed frame. Matrix $R(\psi)$ is the rotation matrix given by

$$R(\psi) = \begin{bmatrix} cos(\psi) & -sin(\psi) & 0 \\ sin(\psi) & cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

Dynamic equations of a 3-DOF vessel model, describing its motions due to forces and torques generated by ship's actuators, can be written as (Fossen (2011)):

$$M\dot{\nu} + C(\nu)\nu + D(\nu)\nu = \tau + w. \tag{2}$$

Here, M is the body inertia matrix, which is the sum of rigid-body mass and hydrodynamic added mass. The $C(\nu)$ matrix contains nonlinear terms due to the Coriolis and centripetal effects. The matrix $D(\nu)$ contains hydrodynamic damping or drag forces. The vector $\tau = [F_x,\ F_y,\ M_z]^\top$, captures forces and moment produced by the actuators, where F_x, F_y, and M_z are respectively the forces and moment that act on the surge, sway and yaw dynamics. We assume that the control input τ is constrained to lie inside the compact set $\mathcal{U}$, *i.e.*,

$$\mathcal{U} = \{\tau \in \mathbb{R}^3 \mid -\tau_{\max} \leq \tau \leq \tau_{\max}\}.$$

Note that $\mathcal{U}$ represents the physical limits of the actuators. At last, w is a term encompassing all external disturbances such as ocean currents, wind and wave; it also includes any model mismatches that the system may have. We assume that $w(t)$ is bounded, *i.e.*,

$$\|w(t)\|_2 \leq w_{\max}$$

for some $w_{\max} > 0$.

Problem statement

Let $\bar{p}^I(t) = [\bar{\eta}(t), \bar{\nu}(t)]^\top$, $p^I(t) = [\eta(t), \nu(t)]^\top$ and $p^I_{tg} = [\eta_{tg}, 0, 0, 0]^\top$ be the nominal (undisturbed), actual and target state vectors respectively, having its three first components written in the inertial frame and its three last components written in the body-fixed frame. The main objective of this paper is to design a control policy such that $p^I(t)$ will be maintained inside an ellipsoid centered

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around $\bar{p}^I(t)$ in the presence of the bounded disturbance $w(t)$, and under the input constraint $\tau(t) \in \mathcal{U}$, which is to be satisfied for all $t \geq 0$. In particular, as t goes to infinity, $\bar{p}^I(t)$ will tend to pItg asymptotically, forcing $p^I(t)$ to be contained in an ellipsoid centered around p^I_{tg}. More specifically, the control objective is to make

$$\lim_{t\to\infty} \|p^I(t) - p^I_{tg}\| \leq \epsilon$$

for some $\epsilon > 0$.

Main results

This section proposes a tube-based MPC control law to solve the DP problem.

Coordinate transformation and linearization

Consider the coordinate transformation

$$e = R(\psi)^\top(\eta - \eta_{tg}), \tag{3}$$

which expresses the tracking error $\eta-\eta_{tg}$ in the body-fixed frame (Fossen (2011)). Using (1), the dynamic equation of the body-fixed tracking error e is given by

$$\dot{e} = -S(r)e + \nu, \tag{4}$$

where $S(r)$ is the skew-symmetric matrix defined as

$$S(r) = \begin{bmatrix} 0 & -r & 0 \\ r & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

For control design, a standard linearization of (2) and (4) around $e_{\text{eq}} = [0,0,0]^\top$ and $\nu_{\text{eq}} = [0,0,0]^\top$ yields:

$$\dot{p} = Ap + B\tau + B_w w, \tag{5}$$

where:

$p = [e,\nu]^\top$, $A = \begin{bmatrix} 0 & I \\ 0 & -M^{-1}D_l \end{bmatrix}$ and $B = B_w = \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix}$

The matrix I denotes the 3x3 identity matrix, 0 is the zero matrix of compatible size and D_l is the linear part of the damping matrix $D(\nu)$. The linearization adopted in this work can be justified by the assumption that the DP task will be performed in low speed. A linear model is then a reasonable approximation in such cases, as quadratic and higher order components in $C(\nu)\nu$ and $D(\nu)\nu$ become negligible (chapt. 7 - Fossen (2011)).

Tube-based MPC design

We briefly introduce the main ideas behind tube-based MPC. The nominal system of (5) is described by

$$\dot{\bar{p}} = A\bar{p} + B\bar{\tau}, \tag{6}$$

where the bar on top of a variable denotes a system not considering external disturbances. The error between the actual and nominal states is $z = p - \bar{p}$ and satisfies

$$\dot{z} = Az + B(\tau - \bar{\tau}) + B_w w. \tag{7}$$

The basic idea of the tube MPC approach is to decompose the computation of a receding-horizon control law into (i) a deterministic MPC problem which uses the nominal dynamics model in (6) to compute a desired state and control trajectory pair $(\bar{p}(t), \bar{\tau}(t))$ over a finite time horizon $[t, t+T]$, and (ii) a feedback control problem that provides a control policy to keep the actual state $p(t)$ close to $\bar{p}(t)$ (Limon et al. (2010)). More precisely, the tube-based MPC technique will use (6) and (7) in order to construct the following input signal

$$\tau(t) = \bar{\tau}(t) + Kz(t). \tag{8}$$

The first term in (8), is the nominal input $\bar{\tau}(t)$ and the second one is the ancillary feedback input $Kz(t)$. To make sure that $\tau(t)$ respects the original input constraints imposed by thrusters, the total input available to the system will be divided into the two terms above during the control design phase. First, the ancillary feedback input gain K will be designed offline by the solution of an LMI. The input capacity not used by Kz will be made available to the nominal input component which will be calculated by an MPC. This process will rely on the set difference computation, in order to "subtract the worst" possible input set defined by the Kz input usage, from the original input constraints, leaving the remainder input capacity as the constraint defining the available input that can be used by the nominal input.

Ancillary feedback synthesis

We now formulate the design of the ancillary controller gain K as a semidefinite program. Assume that there exists a positive definite matrix X, a non-square matrix Y , and scalars $\lambda, \mu > 0$ such that

$$\begin{bmatrix} (AX+BY)^\top + AX + BY + \lambda X & B_w \\ * & -\mu I \end{bmatrix} \le 0.$$

Then, according to Lemma 2 in Yu et al. (2013), the set

$$\Omega := \left\{ z \;\middle|\; z^\top P z \le \frac{\mu w_{\max}^2}{\lambda} \right\} \tag{9}$$

is a robust invariant set for the error system (7), where $P = X^{-1}$ and the ancillary feedback gain is calculated as

$$K = YX^{-1}.$$

Nominal MPC formulation

Using (6), the nominal MPC problem solved at the discrete time instant t_k is (Yu et al. (2013)): minimize

$$\int_{t_k}^{t_k+N} \left(\bar{p}(s)^\top Q \bar{p}(s) + \bar{\tau}_k^\top(s) R \bar{\tau}(s) \right) ds + \bar{p}(t_k+N)^\top Q_f \bar{p}(t_k+N)$$

subject to

$$\begin{array}{ll} \dot{\bar{p}}(t) = A\bar{p}(t) + B\bar{\tau}(t), & t \in [t_k, t_k+N] \\ \bar{\tau}(t) \in \bar{\mathcal{U}}, & t \in [t_k, t_k+N] \\ \bar{p}(t_k+N) \in \mathcal{X}_f. & \end{array} \tag{10}$$

Here, N is the prediction horizon, Q is the state penalty matrix, R is the input penalty matrix, Q_f is the terminal penalty matrix, and $\mathcal{X}_f$ is the terminal set constraint. The set $\bar{\mathcal{U}}$ is the "reduced" input set constraint, defined as

$$\bar{\mathcal{U}} = \mathcal{U} \ominus K\Omega,$$

where Ω is the invariant set calculated in (9). Note that the matrix Q_f and terminal set $\mathcal{X}_f$ can be designed together to ensure nominal MPC stability (Cannon and Kouvaritakis (2016)). In this work, matrices Q and R have been chosen to be diagonal and positive definite. The penalty matrix, due to the DP task, has been chosen to penalize more heading variations about the target and less the remaining states, while R has been chosen to have small entries when compared to Q.

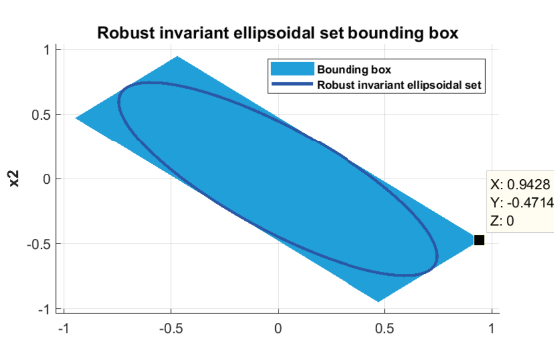

Figure 1: Bounding box enclosing the set $x^T\Omega x \le 1$

Set difference

Next, we describe how can we efficiently compute the set $\bar{\mathcal{U}}$. Consider the H-representation (half-space representation) of two polytopes V and W, defined as

$$V = \{x \in R^n \mid A_v x \le b_v\},$$
$$W = \{x \in R^n \mid A_w x \le b_w\}.$$

Then, one efficient approach to compute the Pontryagin set difference of V and W is

$$V \ominus W = \{x \in R^n \mid A_v x \le b_v - \mathcal{H}(V,W)\}, \tag{11}$$

where the $\mathcal{H}$ operation is defined as

$$\mathcal{H}_i(V,W) = \max_{x \in W} [A_v]_i x$$

with $[A_v]_i$ being the ith row of the matrix A_v (Borrelli et al. (2017)).

To use this approach for computing $\bar{\mathcal{U}}$, first, we find the H-representation of sets $\mathcal{U}$ and $K\Omega$. It is straightforward to show that the original box input constraint imposed by thrusters can be written as

$$\mathcal{U} = \left\{ x \in R^3 \;\middle|\; \begin{bmatrix} I \\ -I \end{bmatrix} x \le \begin{bmatrix} \tau_{max} \\ \tau_{max} \end{bmatrix} \right\}$$

Since Ω is an ellipsoidal invariant set, we consider the bounding box of Ω, the set Ω_b as follows

$$\Omega_b = \left\{ x \in R^6 \;\middle|\; \begin{bmatrix} J^T \\ -J^T \end{bmatrix} x \le \begin{bmatrix} \Lambda_b \\ \Lambda_b \end{bmatrix} \right\}$$

Here, J is the matrix of normalized eigenvectors coming from the decomposition $P = J\Lambda J^T$, Λ is a diagonal matrix assumed to contain the eigenvalues of P, and Λ_b is a diagonal matrix containing the square root of the ratio between $\frac{\mu w_{max}^2}{\lambda}$ and the eigenvalues appearing in the diagonal entries of Λ. For instance, using the decomposition in the ellipsoidal set $x^T\Omega x \le 1$, with

$$\Omega = \begin{bmatrix} 5 & 4 \\ 4 & 5 \end{bmatrix} \text{ and } x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

would produce a bounding box as in Figure 1.

It follows from (11) that the reduced input constraint $\bar{\mathcal{U}}$ can be calculated as:

$$\bar{\mathcal{U}} = \left\{ x \in R^3 \;\middle|\; \begin{bmatrix} I \\ -I \end{bmatrix} x \le \begin{bmatrix}\tau_{max}\\ \tau_{max}\end{bmatrix} - \begin{bmatrix}\max(KV(\Omega_b)) \\ |\min(KV(\Omega_b))|\end{bmatrix} \right\},$$

where $V(\Omega_b)$ is the vertex enumeration operation of Ω_b (Borrelli et al. (2017)). Implementation of this procedure will typically result in the sets as shown in Figure 2.

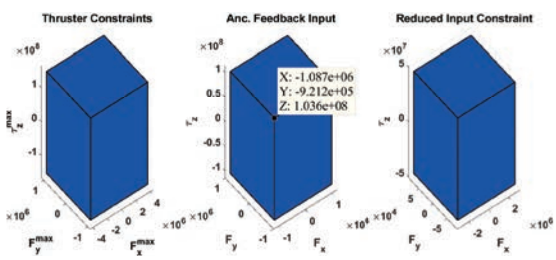

Figure 2: Left-hand set ($\mathcal{U}$), middle set ($K\Omega_b$) and righthand set $\bar{\mathcal{U}} = \mathcal{U} \ominus K\Omega_b$

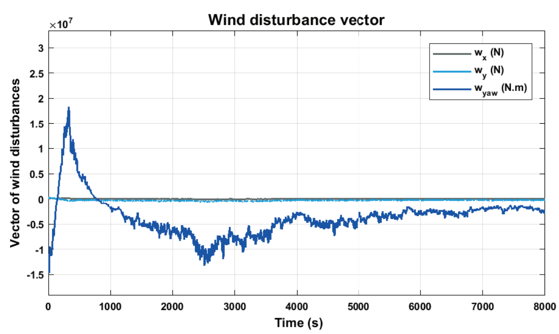

Figure 3: Wind disturbance generated during simulation

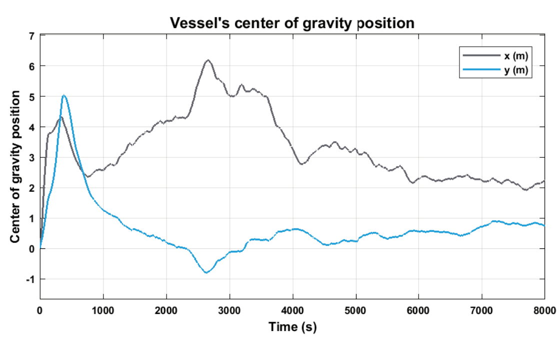

Figure 4: Vessel's center of gravity position

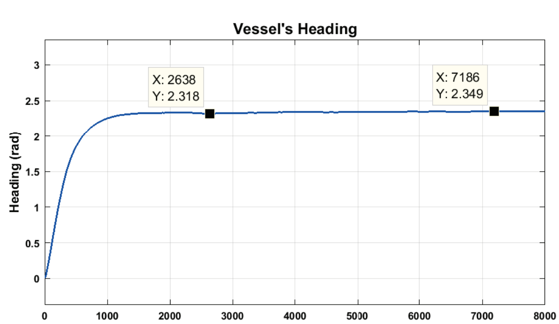

Figure 5: Heading angle of the vessel

The analytical approach above has yielded important benefits for the tube MPC design when comparing to some packages capable of performing set differences. In special, when the eigenvalues of the P matrix differ a lot in order of magnitude, these packages could generate empty sets, when the set difference operation should return a nonempty set. The adoption of this technique could, among other benefits, reduce the number of empty set differences calculated incorrectly.

Simulation results

The method presented will be evaluated by numerical simulation of the technique applied to a non-linear vessel model described by (1) and (2). Simulations done in Matlab/Simulink were performed in a real sized vessel having a length of 294 meter, a beam of 37.9 meter, and a draft of 8 meter. We assume that measurements of all states including position and velocity vectors are available.

For simulation purposes, it was required for the vessel to change its heading angle from 0° to 135° while its center of gravity position should be kept on the same place during the rotation. The limits imposed on the input τ generated by the thrusters can be approximated by the box constraint

$$\begin{bmatrix} -4.10^6 \\ -1.10^6 \\ -1.5.10^8 \end{bmatrix} \le \begin{bmatrix} F_x \\ F_y \\ M_z \end{bmatrix} \le \begin{bmatrix} 4.10^6 \\ 1.10^6 \\ 1.5.10^8 \end{bmatrix}.$$

External disturbances consisting of wind in different directions entering the system can be seen in Figure 3. The wind disturbance vector was chosen so that its norm is smaller than 2.10^7, but has three different magnitude components entering the nonlinear vessel. Wind disturbance components w_x and w_y have an order of magnitude of 10^5 while w_{yaw} has an order of magnitude of 10^7.

The vessel's center of gravity position and heading under these disturbances are shown on Figure 4 and Figure 5, respectively. These variables have final values close to the desired target values. The vessel's center of gravity position, for instance, moves according to the external disturbance although is maintained relatively close to the goal during the whole simulation as desired. Heading values, which seem to be constant after reaching steady state, is varying according to the external disturbance as well, albeit in a very contained manner, as seen on two different instants on

Figure 4. This behaviour reflects the ancillary feedback gain solution found by the LMI which penalizes more deviations in heading and yaw when compared to other states.

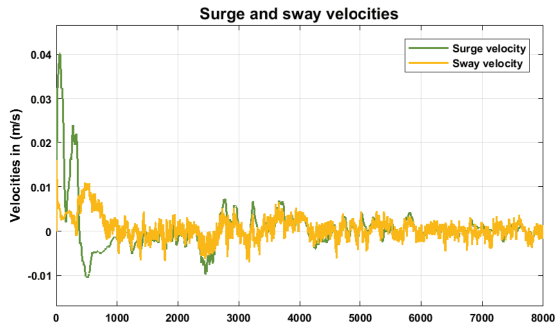

Figure 6: Surge and sway velocities in meter per second

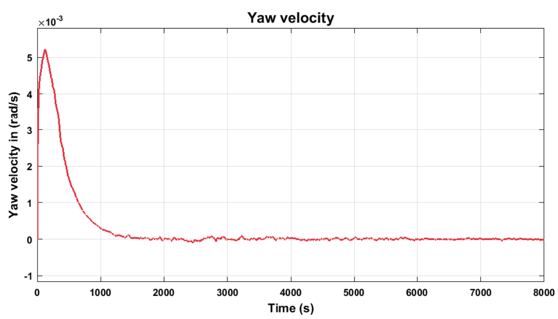

Figure 7: Yaw velocity in radian per second

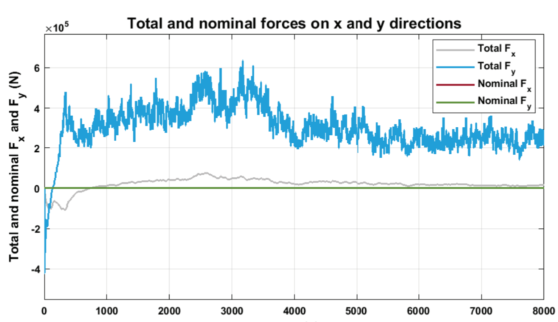

Figure 8. Total values F_x and F_y and its respectives nominal contributions $\bar{F}_x$ and $\bar{F}_y$

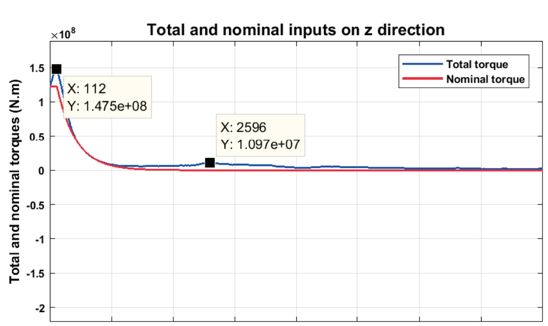

Figure 9: Total value M_z and its respective nominal contribution $\bar{M}_z$

The settling time (around 1900s on Figure 5) is in part defined by the choice of the weights in the matrices Q, R, so as on the parameter λ. In general the higher the weights in Q and λ and the "cheaper the control", the faster (up to a limit) the system settles. It is important to note, on the other hand, that the faster the system is required to settle, the farther away from the assumption of low speed operation (allowing the linearization procedure) the system will be, producing therefore a trade-off.

On Figure 6 surge and sway velocities are depicted while on Figure 7 the yaw velocity is shown. The assumption of low speed DP has been a reasonable one as can be seen by the graphs.

The total input τ and its nominal contributions $\bar{\tau}$ calculated by the nominal MPC can be seen in Figure 8 for the x and y directions, and in Figure 9 for the z direction. It can be seen that τ respects the imposed limits on the three directions during the whole simulation time. At this point, some remarks are relevant. First, note that the ancillary feedback in Figure 8 and in Figure 9 is the difference between total and nominal inputs. In Figure 8, the nominal forces $\bar{F}_x$ and $\bar{F}_y$ are almost zero, leaving the total forces F_x and F_y to be constructed solely by its ancillary feedback counterparts. On the other hand, M_z in Figure 9, is in its majority constructed by $\bar{M}_z$. This happens due to the structure obtained from the linearized dynamics which describes that a turn in the z direction has no effect on the x and y directions. Thus, the act of turning the vessel will be reflected only on $\bar{M}_z$ whereas the rejection of external disturbances and mismatches between the nonlinear model and the linearized version will reflect upon the ancillary feedback portions in the x, y and z directions.

Conclusion and future direction

In this paper, a robust MPC technique for dynamic positioning of marine vessels has been proposed. A nonlinear vessel model is linearized and used in the tube-based MPC formulation. The designed controller is capable of performing the desired task under bounded external disturbances while respecting input constraints. Simulation results have shown that the controller can successfully drive and maintain the vessel close to the target point under disturbance.

There are some points which can be further strengthened in this type of approach, opening space to interesting future directions. First, under the developed formulation, it would be interesting to better understand the mentioned tradeoff and how to optimally tune the values of Q, R and λ, in order to extract the best vessel behavior. It would also be very useful to compare such method, under some metric, to other types of robust controllers in order to see how they would perform against each other. Finally, in order to relax the assumption of low speed application and the usage of system linearization, it would be interesting to develop a new formulation using a nonlinear tube MPC technique, as presented in Singh et al. (2017) for instance, in order to see how well such task would be performed.

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Nonlinear MPC for combined motion control and thrust allocation of ships

For future autonomous marine vessels, better understanding of the ship's behavior and control performance will be essential.

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Traditional motion control systems for ships decouple the problem into high-level motion control of the ship and thrust allocation to achieve the desired control action through the available actuators. The benefit is a segmented software, aiding in development and commissioning. The drawback of this decoupling is that the high-level controller at best has an approximate model of the capabilities in the thruster system. This typically leads to a mismatch between desired and achieved force especially when the control becomes aggressive.

In this paper, a model predictive controller is proposed to solve both tasks simultaneously and overcome this drawback. The controller is based on a low-speed ship and thruster model and the resulting optimization problem is solved using the ACADO toolkit. A simulation study of a supply vessel with only two thrusters is presented to investigate the behavior of the proposed controller in aggressive low speed maneuvering. The results show that there are benefits to incorporating the proposed controller.

When it comes to autonomous vessels, motion control is a task of particular interest. It deals with the design of control laws that allow the ship to perform specific tasks, such as keeping a position and heading angle, tracking way-points, or following desired paths.

For low speed, the motion control system (MCS) is generally decoupled into a high-level controller, which computes forces, and torque to be exerted on the ship and thrust allocation (TA), which is responsible for distributing the control effort among available actuators (Sørrensen, 2011).

Design of high-level controllers for marine vessels have been widely studied in the literature using different approaches ranging from PID to nonlinear controllers (Fossen, 2011). One important aspect is to explicitly account for physical constraints on forces and torques generated by ship actuators. In general, either such constraints are completely neglected, or the controller is specially tuned so that they are not violated under desired conditions.

One of the few techniques in the literature which is capable of handling constraints is model predictive control (MPC). An early MPC application for marine vessels is Wahl and Gilles (1998), where rudder saturation was considered in the control design. The use of MPC has been recently explored for dynamic positioning (Hvamb, 2001; Sotnikova and Veremey, 2013), trajectory tracking (Zheng et al., 2014), and path following of marine vessels (Li et al., 2009).

In applications where TA is used, vessels are commonly over-actuated. The TA is usually formulated as a constrained optimization problem which search for the best solution within physical limitations on actuators, while minimizing some user-defined criterion, for example, consumed power. To achieve better performance, a recent advance is towards MPC-based TA algorithms. This allows the algorithm to optimize rate limited states in the long run, to reduce the power consumption as well as reducing the environmental disturbances in the thruster commands (Skjong and Pedersen, 2017).

This decoupled approach offers the advantage of a modular design where the high-level controller can be designed without detailed knowledge about the vessel's actuator configuration (Johansen and Fossen, 2013). However, this also implies that the generalized force command does not consider the physical limitations of the thruster system, such as limited rotation rate of azimuth thrusters and asymmetric efficiency. This typically give a mismatch between commanded and desired force. To counteract this problem, Veksler et al. (2016) combined the high-level controller and TA into one MPC algorithm to achieve optimal control of the thrusters for a DP application.

In this work, similarly to Veksler et al. (2016), a single MPC controller is used. However, here, the focus is on transient behavior and velocities close to the boundary of low-speed motion control rather than the DP application. Moreover, the applications of interest are vessels that have fewer actuators than a typical DP vessel. Examples of applications could be automated approaches for cruise vessels or low-speed path following for ferries.

Ship model

The notation in this paper will be adopted from Fossen (2011). Here, the ship model is only summarized, for details, the interested reader is referred to Fossen (2011) or Perez (2005) and references therein.

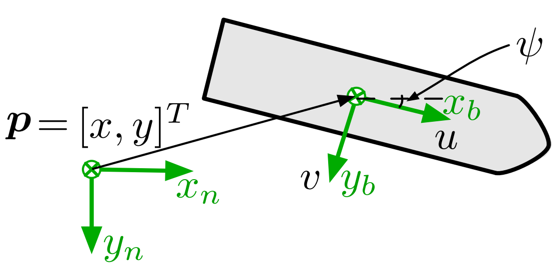


Figure 1: Definition of coordinate systems and velocities

Ship dynamics

This paper regards controlling the position and heading of a ship on the ocean surface at low speed and only the horizontal 3 degrees of freedom (DOF) motion will be considered. The motion of the ship is described using two coordinate systems, a body-fixed system, which is attached to the ship and an Earth-fixed system, which is assumed to be inertial, see Figure 1. The body-fixed generalized velocity is described by $\boldsymbol{\nu} = [u\ v\ r]^T$ and the Earth-fixed generalized position is described by $\boldsymbol{\eta} = [x\ y\ \psi]^T$. Here, u is the surge velocity, v is the sway velocity, r is the yaw velocity, x and y is the position in a North-East-Down (NED) coordinate system and ψ is the heading. The relationship between the velocity and the position is purely geometric and is described by

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu} \tag{1}$$

where the rotation matrix is given by

$$\boldsymbol{R}(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

A model of the kinetic motion for ships can be derived using rigid-body mechanics and theory of hydrodynamics (Fossen, 2011). Due to the low speed and the 3 DOF considered, a model describing the kinetics is given by

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{D}\boldsymbol{\nu} = \boldsymbol{\tau}_c + \boldsymbol{\tau}_{\text{env}} \tag{3}$$

where $\boldsymbol{M}$ is the matrix of total inertia including added mass, $\boldsymbol{D}$ is the linear damping matrix, $\boldsymbol{\tau}_c$ is the forces exerted by the thrusters and $\boldsymbol{\tau}_{\text{env}}$ is the environmental forces acting on the ship (Fossen, 2011). In this paper, the focus is on maneuvering the ship and for this reason, the environmental forces will be neglected.

Thrusters

Marine vessels can be equipped with a range of different actuators depending on the intended use. These include propellers, water jets, sails and rudders to name a few (Molland et al., 2011). The purpose of the actuator is to produce a controlled force on the vessel to obtain the desired movement. In low speed motion control, a commonly used actuator is the azimuth thruster (Lewandowski, 2004). It comprises of a propeller mounted on a hub able to rotate (azimuth) freely in the horizontal plane. The control forces and moments created by a thruster are dependent on its location and orientation and on the fluid velocity around the propeller, which in turn relate to the velocity of the ship and the speed of the propeller (Whitcomb and Yoerger, 1999). Moreover, some actuators, such as rudders, will create forces by the water ow. Thus, in the general case, a model of the thrusters is

$$\boldsymbol{\tau}_c = \boldsymbol{h}(\boldsymbol{\nu}, \boldsymbol{u})$$

where $\boldsymbol{u}$ is a vector of control signals, such as thruster angles or propeller speeds. For low speed, the velocity dependency is usually neglected and $\boldsymbol{h}$ typically takes the form (Fossen and Johansen, 2006)

$$\boldsymbol{\tau}_c = \boldsymbol{T}(\boldsymbol{\alpha})\boldsymbol{f}(\boldsymbol{n}) \tag{4}$$

where the control signals u have been split into thruster angles $\boldsymbol{\alpha}$ and propeller speeds $\boldsymbol{n}$. Moreover, $\boldsymbol{f}(\boldsymbol{n}) \in \mathbb{R}^M$ is a vector of thrust magnitude for each thruster, and

$$\boldsymbol{T}(\boldsymbol{\alpha}) = [\boldsymbol{t}_1(\alpha_1), \ldots, \boldsymbol{t}_M(\alpha_M)] \quad \in \mathbb{R}^{n \times M}$$

describes the geometry of the thruster configuration. In 3 DOF, the columns of $\boldsymbol{T}(\boldsymbol{\alpha})$ can be described by

$$\boldsymbol{t}_i(\alpha_i) = \begin{bmatrix} \cos\alpha_i \\ \sin\alpha_i \\ l_{x,i}\sin\alpha_i - l_{y,i}\cos\alpha_i \end{bmatrix}, \quad i = 1, \ldots, M \tag{5}$$

where $l_{x,i}$ and $l_{y,i}$ are the moment arms given in the bod-fiyxed coordinate system and α_i describe the orientation, taken positive clock-wise from the body-fixed x-axis.

For low speed motion control, the thrust f_i produced by the i^{th} thruster is assumed to be proportional to the square of the rotational velocity of the propeller. More precisely, under bollard-pull condition (stationary vessel), a model of a symmetrical propeller's steady-state axial thrust f_i of the i^{th} thruster is given by

$$f_i = k_i n_i |n_i|, \quad i = 1, \ldots, M \tag{6}$$

where k_i is a constant and n_i is the rotational speed of the propeller (Whitcomb and Yoerger, 1999). Subsequently, the thrust vector $\boldsymbol{f}(\boldsymbol{n})$ in (4) can be written as

$$\boldsymbol{f}(\boldsymbol{n}) = \begin{bmatrix} f_1(n_1) \\ \vdots \\ f_M(n_M) \end{bmatrix} = \boldsymbol{K} \begin{bmatrix} n_1|n_1| \\ \vdots \\ n_M|n_M| \end{bmatrix} \tag{7}$$

where $\boldsymbol{K} \in \mathbb{R}^{M \times M}$ is a diagonal matrix with k_1, k_2, ..., k_M on the diagonal.

Motion control for ships

The typical application for ships employing the decoupled motion control described in Section 1 is Dynamic Positioning (DP) where the demands on performance and reliability usually are very strict. A typical DP capable ship come equipped with a redundant set of actuators. This means there are several ways of coordinating the actuators to produce the same net control force on the ship. The redundant actuators also put less emphasis on rotating the thrusters since they can be oriented in such a way that it is possible to quickly generate force and torque in any direction. In this paper, the focus is rather on another class of vessels equipped with fewer actuators where the transient behavior is of importance, for instance, low-speed path following for ferries. This imply that the freedom of the possible thrust is limited, since at any point in time there may be only a few, or not any, ways of coordinating the actuators to produce the desired force.

Before we present the proposed combined model predictive controller for thrust allocation and motion control, theory for model predictive control and general description of thrust allocation will be presented.

Model predictive control

Model Predictive Control (MPC) is an advanced control strategy commonly found in the process industry which uses an explicit model of the system to predict the future behavior. This predictive capability allows solving optimal control problems on-line, where tracking error is minimized over a future horizon, possibly subject to constraints on the manipulated inputs and states (Maciejowski, 2002). In continuous-time, the MPC problem can be written as

$$\min_{\boldsymbol{u}} \int_{t_0}^{t_0+T} \|\boldsymbol{x}(t) - \boldsymbol{x}_r(t)\|^2_{\boldsymbol{Q}_x} + \|\boldsymbol{u}(t) - \boldsymbol{u}_r(t)\|^2_{\boldsymbol{Q}_u}\, dt + \|\boldsymbol{x}(t_0+T) - \boldsymbol{x}_r(t_0+T)\|^2_{\boldsymbol{R}_x} \tag{8a}$$

$$\text{s.t.} \quad \boldsymbol{x}(t_0) = \boldsymbol{x}_0 \tag{8b}$$

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t), \boldsymbol{u}(t)), \quad \forall t \in [t_0, t_0+T] \tag{8c}$$

$$\boldsymbol{g}(t, \boldsymbol{x}(t), \boldsymbol{u}(t)) \le 0, \quad \forall t \in [t_0, t_0+T]. \tag{8d}$$

90

where $\boldsymbol{Q}_x \geq 0$, $\boldsymbol{Q}_u > 0$, and $\boldsymbol{R}_x \geq 0$ are weight matrices. Moreover, $\boldsymbol{x} \in \mathbb{R}^{n_x}$ is the state vector, $\boldsymbol{u} \in \mathbb{R}^{n_u}$ is the control input, x_0 is the current value of the system state, and $\boldsymbol{x}_r$ and $\boldsymbol{u}_r$ are desired reference trajectories for system state and control input, respectively.

To solve the MPC problem (8) using numerical optimization methods, the cost function and differential equations corresponding to the ship dynamical system need to be discretized. At each sampling instant, the current state is used to initialize the problem and the optimization problem is solved over the horizon $[t_0, t_0+T]$. The solution is a sequence of control inputs and only the first element in the sequence $u^\star(t_0)$ is applied to the system. This process is repeated each sample.

Thrust allocation
The objective of the thrust allocation (TA) is to realize the desired control force by coordinating the available thrusters. The more thrusters the ship is equipped with, the more combinations of inputs may be used. The problem is naturally formulated as a constrained optimization problem, where the objective function may be to minimize the total energy consumption and wear and tear of the actuators, while the constraints describe the objective and physical limitations on the actuators (Johansen and Fossen, 2013). A general problem formulation is

$$\min_{\boldsymbol{u},\boldsymbol{s}} \quad p(\boldsymbol{\eta},\boldsymbol{\nu},\boldsymbol{u},\boldsymbol{s},t) \tag{9a}$$
$$\text{s.t.} \quad \boldsymbol{\tau}_c^d - \boldsymbol{h}(\boldsymbol{\eta},\boldsymbol{\nu},\boldsymbol{u},t) = \boldsymbol{s} \tag{9b}$$
$$\boldsymbol{g}(\boldsymbol{\eta},\boldsymbol{\nu},\boldsymbol{u},t) = 0 \tag{9c}$$

where p is some cost function of the states $(\boldsymbol{\eta},\boldsymbol{\nu})$, inputs $\boldsymbol{u} = (\boldsymbol{n},\boldsymbol{\alpha})$, slack variables $\boldsymbol{s}$ and the time t. The constraint (9b) represent the main priority of the thrust allocation but with the addition of $\boldsymbol{s}$ in case it is not feasible. For low speed, the function $\boldsymbol{h}$ is typically represented by the right hand side of (4).

Finding the global minimum of (9) tends to be di cult since the problem, in general, is non-convex (Fossen and Johansen, 2006). Thus, the algorithm may get stuck in local minima. For rotating and asymmetric thrusters, a thruster may end up stuck producing thrust in reverse of its most efficient direction. To mitigate this, the TA algorithm is usually augmented with external logic determining if it is beneficial to rotate the thrusters (Veksler et al., 2016). Note also that the TA algorithm solves an optimal control problem in similar fashion to the MPC controller described above. In a way, (9) is an MPC formulation with a 1-step prediction horizon.

Combined thrust allocation and motion control
Deviating from the traditional structure, formulating two different optimization problems, we now present a single MPC combining the work of both motion control and TA algorithms similar to Veksler et al. (2016).

From (1), (3) and (4), the combined problem of motion control and TA is formulated as

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu}, \tag{10a}$$
$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{D}\boldsymbol{\nu} = \boldsymbol{T}(\boldsymbol{\alpha})\boldsymbol{f}(\boldsymbol{n}), \tag{10b}$$

with the system states $(\boldsymbol{\eta},\boldsymbol{\nu})$ and control inputs $(\boldsymbol{n},\boldsymbol{\alpha})$. Both inputs $(\boldsymbol{n},\boldsymbol{\alpha})$ are subject to physical constraints. The propeller speeds $\boldsymbol{n}$ are both limited in magnitude and rate while the thruster angles $\boldsymbol{\alpha}$ are only limited in rate. Combining (10) with the constraints, the continuous-time nonlinear optimization problem is formulated as

$$\min_{\dot{\boldsymbol{n}},\dot{\boldsymbol{\alpha}}} \int_0^{T_sN} (\|\boldsymbol{\eta}-\boldsymbol{\eta}_r\|^2_{\boldsymbol{Q}_\eta} + \|\boldsymbol{\nu}-\boldsymbol{\nu}_r\|^2_{\boldsymbol{Q}_\nu} + \|\boldsymbol{n}\|^2_{\boldsymbol{Q}_n} + \|\dot{\boldsymbol{\alpha}}\|^2_{\boldsymbol{Q}_{d\alpha}} + \|\dot{\boldsymbol{n}}\|^2_{\boldsymbol{Q}_{dn}})dt + \text{final cost} \tag{11a}$$
$$\text{s.t.} \quad \dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu} \tag{11b}$$
$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{D}\boldsymbol{\nu} = \boldsymbol{T}(\boldsymbol{\alpha})\boldsymbol{f}(\boldsymbol{n}) \tag{11c}$$
$$\underline{\boldsymbol{n}} \leq \boldsymbol{n} \leq \bar{\boldsymbol{n}} \tag{11d}$$
$$|\dot{\boldsymbol{\alpha}}| \leq \bar{\dot{\boldsymbol{\alpha}}} \tag{11e}$$
$$\underline{\dot{\boldsymbol{n}}} \leq \dot{\boldsymbol{n}} \leq \bar{\dot{\boldsymbol{n}}} \tag{11f}$$

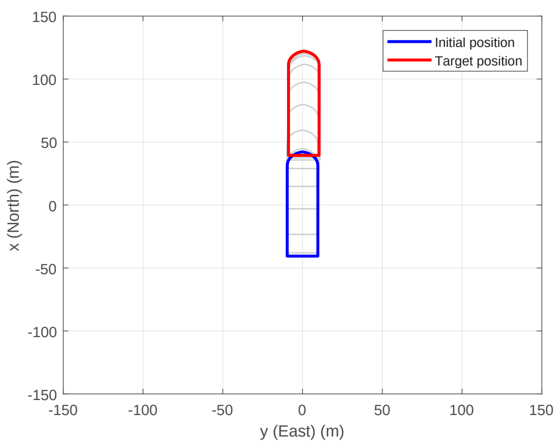
where the final cost contains similar terms as the stage cost. The last two terms in the stage cost penalize the rate of the control inputs to reduce fast changes in the inputs, implying wear and tear reduction on the propulsion equipment. The constraints (11b) and (11c) defines kinematic and dynamic equations of the ship, respectively, while (11d)-(11f) constrain the control inputs.

Combining the high-level controller and TA has several advantages compared to having them separate. For instance, instead of finding bounds on and tuning the weights for the virtual control input $\boldsymbol{\tau}_c^d$, the commissioning engineer may instead

Table 1: Parameters for the thruster models

Parameter	Thruster 1	Thruster 2
l_x	32 m	-32 m
l_y	0 m	0 m
Turning rate	±7.2 deg/s	±7.2 deg/s
Available thrust	±1.67 MN	±1.67 MN
Allowed propeller speed	±2 RPS	±2 RPS
Allowed propeller acceleration	±0.08 RPS/s	±0.08 RPS/s

(a) First test case



(b) Second test case

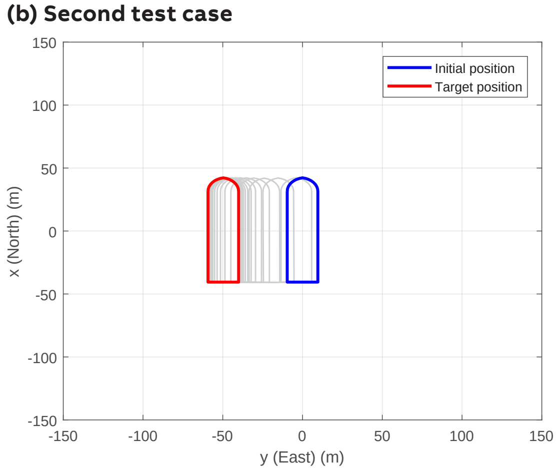


Figure 2: Illustration of the motion in the horizontal plane

Table 2: Summary of test cases and parameters used

Case	Initial position	Initial thruster angles	η_r
1	$[0,\ 0,\ 0]^T$	$[0,\ 0]^T$	$[80,\ 0,\ 0]^T$
2	$[0,\ 0,\ 0]^T$	$[\frac{\pi}{2},\ \frac{\pi}{2}]^T$	$[0,\ -50,\ 0]^T$

use the physical constraints of the thrusters, and tune the weights on $(\boldsymbol{n}, \boldsymbol{\alpha})$ to prioritize among them. Moreover, the trade-o between tracking accuracy and the variation in the actuator inputs is more intuitive since they both appear in the cost function. Further, with a long enough prediction horizon, the MPC should be able to find the long-term benefit of having the thrusters point in the right direction, thus not requiring an external algorithm as mentioned in Section 3.2. Finding the global minimum of (11) is difficult however, and the use of fast end accurate solvers is key.

Implementation

The MPC formulation (11) describe a time-continuous nonlinear optimization problem. As mentioned in Section 3.1, solving it on a computer requires discretizing the problem and using an optimization solver for the resulting problem. Solving a nonlinear problem requires some extra care and, depending on the number of states/inputs and length of the prediction horizon, the optimization problem typically becomes large and time-consuming to solve. In this work, the MPC was developed using the MATLAB interface for the open-source ACADO toolkit (Houska et al., 2011), with the optimization problem solved by QPOASES (Ferreau et al., 2014). The ACADO toolkit allows the user to input the time-continuous formulation, automatically handling the discretization and exporting a fast tailor made solver based on the Real Time Iterations (RTI) scheme. The RTI scheme essentially works by linearizing the problem around the current state estimate and solving one QP in each iteration, thus making it only marginally slower than linear MPC (Gros et al., 2016). The ACADO toolkit does not support the absolute value formulation used in (6). To solve this issue and get a differential function, the absolute value was approximated as

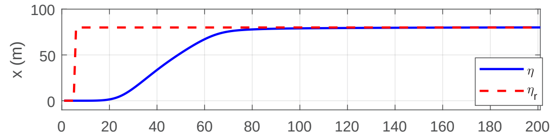
$$|x| \approx \sqrt{x^2 + \varepsilon}$$

Simulation results and discussion

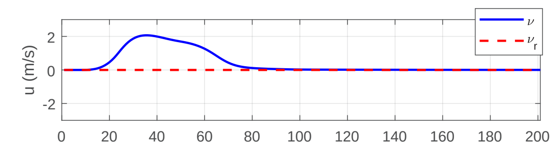
A small ship with two thrusters were chosen to test the proposed motion control system. This configuration was chosen to highlight the potential benefits of the proposed algorithm compared with the issues raised in Section 3.

The simulation model was implemented in Simulink and was based on the supply vessel model available

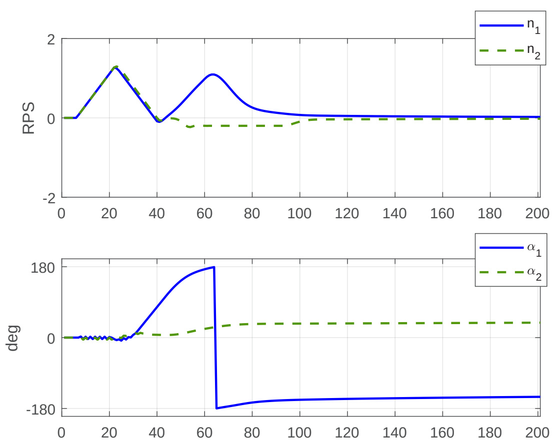
(a) Position of the vessel along x_n



(b) Surge velocity



(c) Inputs (n, α) for the thrusters. The angles are wrapped to ±180°.



(d) Force exerted on ship τ_c and calculated force to be exerted on the ship using (4), i.e. the internal force in the MCS. The slight mismatch is due to the neglected velocity dependence of the thrusters.

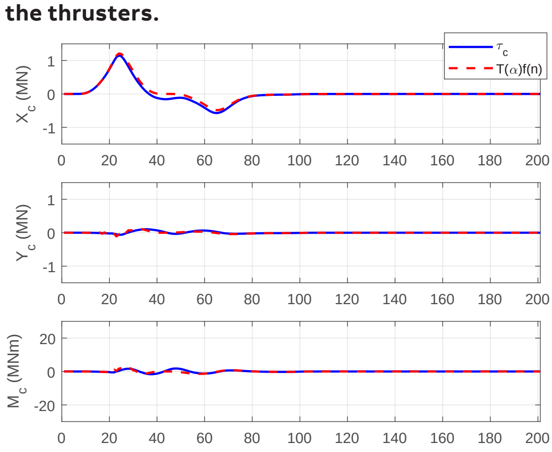


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Figure 3: Results of the first test case. The deviation from the reference in the DOF not shown in Figure 3a and Figure 3b were deemed negligible and omitted.

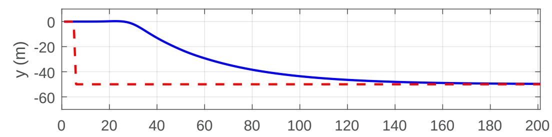
in the MSS hydro toolbox (Fossen and Perez, 2004). This vessel is 82.8 m long, 19.2 m wide and has a displacement of 6360 tons (Fossen and Perez, 2004). The ship model was coupled with a velocity dependent azimuth thruster model. The velocity dependency models water ow over the propeller and rudder effects due to a rudder like geometry of the azimuth thruster body. Two thrusters were used in the simulation, one in the stern and the other in the bow, both mounted on the center line of the vessel. The azimuth model was asymmetric, meaning that it is more efficient to produce thrust with a positive propeller speed. In Table 1, important parameters of the thrusters are found. Note that there was a model mismatch since the velocity dependency was neglected in the MCS.

To counter the asymmetry of the thrusters, the lower bound on $\boldsymbol{n}$ in the MCS was chosen to a fraction of the specified lower bound in Table 1. This made it more beneficial to turn the thruster around when needing to create an opposite force.

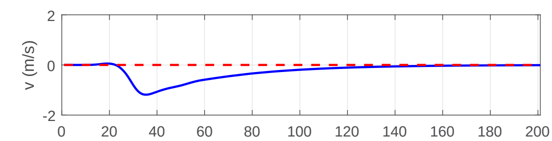
The MCS was tested for a wide range of maneuvers. Out of these, the result for two different cases that highlight key features of the proposed solution are presented. Although the proposed solution supports a time-varying reference in velocity and position, it was deliberately chosen to be simple (step change in position) to focus on the behavior of the MCS rather than the trajectory generation. Figure 2 visualizes the motion of the ship for these test cases. Both maneuvers are quite aggressive with a relatively high acceleration and in the upper bound of the low-speed envelope. In both cases, the velocity reference $\boldsymbol{\nu}_r$ was set to zero while a step in position reference $\boldsymbol{\eta}_r$ occurred at t = 8. The differences between the cases are the position reference and the initial thruster orientations, see Table 2. The sample rate was chosen to 2 Hz with the prediction horizon N = 80. Tuning parameters were kept constant through both cases. They were chosen as to produce aggressive maneuvers, while still retaining the general desired behavior. The worst case execution time of the MCS for any test cases was around 0.5 seconds on a laptop with an Intel i7 processor running at 2.9 GHz with 16 GB of RAM.

In the first case seen in Figure 3, the ship is commanded to move to a position in front of it

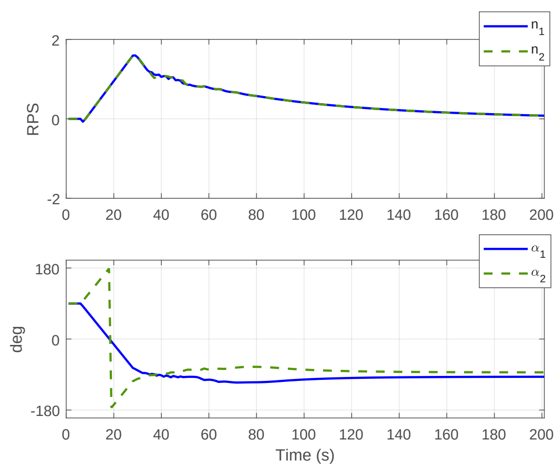
(a) Position of the vessel along x_n



(b) Surge velocity



(c) Inputs (n, α) for the thrusters. The angles are wrapped to ±180°.



(d) Force exerted on ship τ_c and calculated force to be exerted on the ship using (4), i.e. the internal force in the MCS.

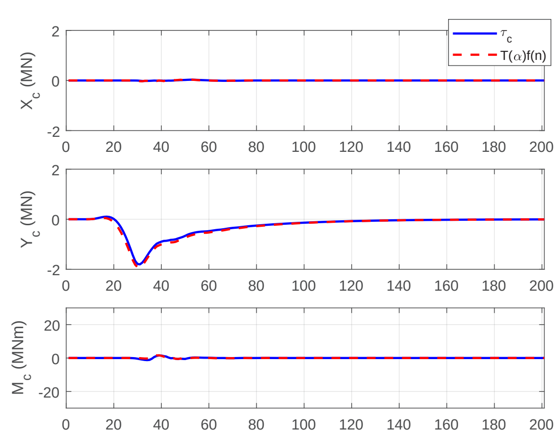


Figure 4: Results of the second test case. The deviation from the reference in the DOF not shown in Figure 4a and Figure 4b were deemed negligible and omitted.

and stop. Thrusters are initially pointing straight forward in the direction of travel. When the step enters, the MCS commands full forward thrust with both thrusters, initially reaching a high speed. After a while, at t = 28, it begins to rotate thruster 2, while simultaneously decreasing n_2 in order to not create too much yaw torque. That is, in anticipation of reaching the target point, the MCS rotates one thruster to maintain in control of the ship. When the thruster is beginning to point in a useful direction, i.e. towards the stern, it accelerates the propeller again to slow down the ship. Meanwhile, the other thrusters reverses slightly to help reduce the speed and correct for yaw- and sway movement. Thus, the MCS manages to overcome the rotation time of the thrusters and stop the ship in time.

This kind of thruster control would be di cult to achieve using a traditional hierarchy for the MCS since the TA, in its usual form only tries to achieve the current desired force. In cases such as this, where the maneuver is aggressive and the ship is not able to generate force in all DOF simultaneously, the performance will most likely degrade with the traditional setup. A force mismatch will occur between what the high-level controller wants and what the TA can deliver, due to the rotation time of the thrusters which is unknown to the high-level controller. Thus, one would have to rely on slower and more conservative maneuvers, where there is room for a deviation between the desired and actual force. This could for instance be achieved by a careful and conservative tuning of the motion controller, or by generating a trajectory known to be achievable.

The second test case can be seen in Figure 4. The ship now has to move in a negative y_b-direction while the thrusters initially are pointing straight in positive y_b. The MCS completes this maneuver by first rotating the thrusters 180 degrees to allow for positive RPM. Since the MPC has knowledge on the physical limitations of the thrusters it will only require a feasible force. In this case, the traditional solution with a one-step TA might get stuck reversing the thrusters or request a large force that is not achievable with the current state of the thrusters. Since the TA only tries to fulfill the current desired force, it will not take into account the long term benefit of having the thrusters point in the right direction.

Conclusion

In this paper, a combined MPC for motion control and thruster allocation was presented. The problem was formulated with a low-speed ship and thruster model and the aim was to improve maneuvering behavior. The MPC problem was implemented with the ACADO toolkit with the RTI scheme. The test result and execution time on the test computer indicate that this problem can be run in real-time on today's hardware.

It appears that the combined MPC offers improvements in control performance compared to capabilities of the traditional decoupled approaches. The combined MPC has full knowledge on the state and limitations of the thrusters and is able to coordinate them more efficiently throughout the control horizon. It accounts for the delay caused by the rotation time of the thrusters when planning the motion. This makes it more robust to different tuning and aggressive maneuvers. Although the behavior was satisfactory, it is di cult to tell if this is the optimal behavior with respect to the objective. Convergence of the solver is not guaranteed and care should be taken to ensure that it does not get stuck in local minima. In the current implementation, the thruster model was kept simple. Future work includes extension of the thruster model to include velocity dependencies and asymmetry. Moreover, the power of the thruster is typically proportional to the cube of the engine speed and more work should be spent on understanding the impact of the quadratic cost function. Finally, the impact of environmental disturbances should be considered in future developments to complement the maneuvering behavior.

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Autonomous docking and navigation using Voronoi diagrams and model predictive control

Autonomous shipping is an emerging field where it will be important to operate a ship without manual intervention.

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Although there are many issues yet to be solved, not the least the legal ones, it is interesting to investigate functions that already now would be possible to use in today's ship operation. One such field is autonomous navigation in narrow areas. This paper presents a study where a ship is docked autonomously while using information only from the final docking position and the harbor geometry. The Guidance, Navigation and Control system (GNC) outlined here is based on a combination of Voronoi diagrams for the waypoint generation and an integrating model predictive controller (MPC) for the path following between waypoints. Simulations demonstrate how the proposed procedure is able to autonomously dock a cruise ship in the South Harbor of Helsinki.

Introduction
The shipping business is subject to major changes in the future. Safety, costs, energy efficiency, and environmental footprint are some of the factors that drive the change. There is also a tendency to decrease the crew size on board due to cost and this type of labor is predicted to be less attractive in the future. With less people and an increased demand for safety and efficiency there is a demand in many situations to use autonomous functions for consistent and predictable behavior. One such situation is when the ship is approaching a harbor where it is going to dock.

A Guidance, Navigation and Control system (GNC) for autonomous or for automated operation could be used for this. Such systems are commonly applied for motion control of vehicles, spacecraft, aircraft, auto-mobiles and underwater vehicles, see [1], [2], [3], and [4]. Examples of such systems could be found already in the 1920s when the heading of a US navy battleship was automatically steered [5].

The guidance system aims to provide a path or trajectory which fulfills some specific requirements, such as minimum time or fuel optimization. There are various strategies for the guidance system, and the most common strategies are target tracking, trajectory tracking and path following [1].

Some traditional approaches for path planning are cell decomposition [6], the roadmap method [7], and potential fields [8]. Voronoi diagram is studied by Bhattacharya et al. [7] for finding a path for vessel navigation along the South American coastline, and the diagram is generated by a set of points which are the edges of obstacles. The advantage of the Voronoi diagram method is that the maximum clearance path can be generated. However, the path is not necessarily the shortest. The potential field method presents potential from obstacles, and high potential will be provided when a vehicle is close to an obstacle.

Once the path is defined in a list of waypoints it is the task of the control system to maneuver the ship along the desired path and finally reach the desired position. There are several approaches for this. Model Predictive Control (MPC) is one approach which has been proposed in [9]. Other methods, such as back-stepping, has also been introduced to control an autonomous ship, see [10] and [11].

A switching control strategy was proposed in [12] where switches between a linear feedforward-feedback strategy and an MPC can bring the vehicle into a desired parking spot. Instead of using waypoint tracking, a path following method was investigated in [13] in order to park a car. However, because the path was predefined, only one case, reverse parking, was studied.

Waypoint tracking is another method for navigation which is popular for autonomous vehicle, see [14], [15] and [16].

Few studies are reported for docking of ships using MPC. Docking procedures for other crafts such as spacecrafts can be found in [17]. However, path following during docking of marine vessels have been reported in [18] and [19].

A method for autonomous operation of a marine vessel is proposed here. In particular, it is a procedure for the automatic docking of a vessel in a harbor where only the final docking position (including the heading) and the geometry of the harbor are known. The method combines the use of Voronoi diagrams for generating a desired path from a set of waypoints and the use of MPC with integral action for following the desired path. The integral action is needed to handle slowly varying disturbances as wind and current. The proposed method for autonomous docking is illustrated by a simulation in the South Harbor of Helsinki where a simulated ship is navigated through a narrow passage and docked. Further details in this study can be found in [20].

Ship modeling

Ship modeling is extensively described in [1] and details of the modeling are referred to this book.

For the control purposes in this paper it is sufficient with a three degree of freedom (3-DOF) model that describes the motions in surge, sway and yaw. The generalized velocity in the body-fixed coordinate system is defined as $\boldsymbol{\nu} = \begin{bmatrix} u & v & r \end{bmatrix}^T$ and the generalized position in an Earth-fixed coordinate is defined as $\boldsymbol{\eta} = \begin{bmatrix} X & Y & \psi \end{bmatrix}^T$. The generalized position and velocity is related by the kinematic model

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu} \tag{1}$$

where the rotation matrix is given by

$$\boldsymbol{R}(\psi) = \begin{bmatrix} \cos(\psi) & -\sin(\psi) & 0 \\ \sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

The ship is assumed to be a rigid body and the kinetics model describing the motion induced by forces is given by

$$\boldsymbol{M}_{\mathrm{RB}}\dot{\boldsymbol{\nu}} + \boldsymbol{C}_{\mathrm{RB}}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau}_{\mathrm{RB}} \tag{3}$$

where $\boldsymbol{M}_{\mathrm{RB}}$ is the rigid-body inertia matrix, $\boldsymbol{C}_{\mathrm{RB}}(\boldsymbol{\nu})\boldsymbol{\nu}$ v represents centripetal and Coriolis force and $\boldsymbol{\tau}_{RB}$ represents the generalized force acting on the rigid body. For 3-DOF motion, this forces is assumed to be given by

$$\boldsymbol{\tau}_{\mathrm{RB}} = \boldsymbol{\tau}_{\mathrm{hyd}} + \boldsymbol{\tau}_{\mathrm{env}} + \boldsymbol{\tau}. \tag{4}$$

where the terms in the right hand side are the generalized forces induced by hydrodynamics, environmental disturbances, and the actuators, respectively.

The hydrodynamics forces are assumed to be given by

$$\boldsymbol{\tau}_{\mathrm{hyd}} = -\boldsymbol{M}_{\mathrm{A}}\dot{\boldsymbol{\nu}} - \boldsymbol{C}_{\mathrm{A}}(\boldsymbol{\nu})\boldsymbol{\nu} - \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} \tag{5}$$

where $\boldsymbol{M}_{\mathrm{A}}$ is the added mass/inertia matrix, $\boldsymbol{C}_{\mathrm{A}}(\boldsymbol{\nu})\boldsymbol{\nu}$ represents centripetal and Coriolis force due to added mass/inertia and the term $\boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu}$ represents hydrodynamic damping.

The ship under consideration is propelled with a combination of Azipods, [21], [22], and tunnel thrusters which gives good maneuverability. The dynamics of the thrusters can be taken into consideration to get better performance. A complete model of the thrusters was deemed too complicated and a simplified model was chosen in this work. A suitable model was proposed in [1] and is given by the saturated first order dynamics

$$T_{\text{thr}}\dot{\boldsymbol{\tau}} + \boldsymbol{\tau} = \text{SAT}(\boldsymbol{\tau}_{\text{low}}, \boldsymbol{\tau}_c, \boldsymbol{\tau}_{\text{high}}) \tag{6}$$

where $T_{\text{thr}} = \text{diag}(T_{\text{surge}}, T_{\text{sway}}, T_{\text{yaw}})$, $\boldsymbol{\tau}_{\text{low}}$ and $\boldsymbol{\tau}_{\text{high}}$ are upper and lower bounds in the different directions, respectively, and τ_c is the command from the control algorithm. The saturation function SAT(·) is acting on each element of the vector individually and each row is given by

$$\text{sat}(l, x, h) = \begin{cases} l, & \text{if } x < l \\ x, & \text{if } l \leq x \leq h \\ h, & \text{if } x > h \end{cases} . \tag{7}$$

Inserting (4) and (5) into (3) and combining it with (2) and (6) give the complete model

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\psi)\boldsymbol{\nu} \tag{8a}$$
$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau} + \boldsymbol{\tau}_{\text{env}} \tag{8b}$$
$$T_{\text{thr}}\dot{\boldsymbol{\tau}} + \boldsymbol{\tau} = \text{SAT}(\boldsymbol{\tau}_{\text{low}}, \boldsymbol{\tau}_c, \boldsymbol{\tau}_{\text{high}}) \tag{8c}$$

where $\boldsymbol{M} = \boldsymbol{M}_{\text{RB}} + \boldsymbol{M}_{\text{A}}$ and $\boldsymbol{C} = \boldsymbol{C}_{\text{RB}}(\boldsymbol{\nu}) + \boldsymbol{C}_{\text{A}}(\boldsymbol{\nu})$. A linear MPC was considered sufficient to solve the control problem. To provide a linear model of the vessel, (8) is linearized about the current position, zero velocity and zero force. This results in the linear state-space model

$$\begin{bmatrix} \dot{\boldsymbol{\eta}}_p \\ \dot{\boldsymbol{\nu}} \\ \dot{\boldsymbol{\tau}} \end{bmatrix} = \begin{bmatrix} \mathbf{0} & \boldsymbol{I} & \mathbf{0} \\ \mathbf{0} & -\boldsymbol{M}^{-1}\boldsymbol{D} & \boldsymbol{M}^{-1} \\ \mathbf{0} & \mathbf{0} & -\boldsymbol{T}_{\text{thr}}^{-1} \end{bmatrix} \begin{bmatrix} \boldsymbol{\eta}_p \\ \boldsymbol{\nu} \\ \boldsymbol{\tau} \end{bmatrix} + \begin{bmatrix} \mathbf{0} \\ \mathbf{0} \\ \boldsymbol{T}_{\text{thr}}^{-1} \end{bmatrix} \boldsymbol{\tau}_c + \boldsymbol{\tau}_{\text{env}} \tag{9}$$

where $\boldsymbol{\eta}_p = [X_p, Y_p, \psi_p]^T$ is the position vector in the linearized model.

Ship control system

The overall system for guidance, navigation, and control of the ship consist of three main components. There is a guidance system for waypoint generation and a control system for trajectory following between waypoints. There is also a navigation system that provides wave filtered observations of the ship positions and velocities transformed to the appropriate coordinate system. The structure is shown in Figure 1.

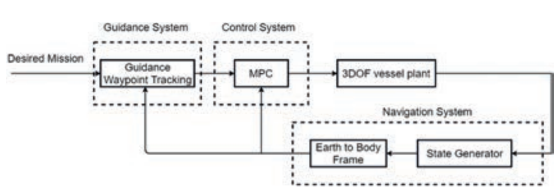

Figure 1: Structure of the simulated guidance, navigation and control system

Voronoi diagrams are used for waypoint generation in the guidance system and the control system for waypoint following is based on Model Predictive Control (MPC).

Guidance System

The potential complexity of the auto-docking problem for a general harbor geometry is a difficult problem to solve for an MPC if only the starting position and the desired final position were supplied. To simplify the task for the MPC and make it more robust to complex geometries, the guidance system will instead generate a list of waypoints which the ship could follow to safely reach its docking position.

One of the main concerns with autonomous operation is how to avoid obstacles. These obstacles can, for instance, be islands and other vessels.

Obstacles are typically classified as static or dynamic obstacles [23]. Static obstacles can be predicted before the path is planned, while dynamic obstacles will appear during the motion. It is assumed to have knowledge of the environment and thus treat the obstacles and other ships as static obstacles.

Here, obstacles will be treated as boundaries, both for the Voronoi diagram generation and later as constraints in the MPC. In most cases, boundaries are not symmetrical and the narrowness of the path is changing. To present the obstacles with one strategy, the path is divided into several parts where each segment has their own set of geometrical constraints.

The path and segments are constructed using a Voronoi diagram which is constructed from a set of predefined points (p_{ix}, p_{iy}) in a plane. The predefined points are given by the geometry of the harbor. First, a set of cells are defined. Every point in a certain cell is closer to the predefined point in this cell than to any other predefined point, i.e. a point (q_x, q_y) lies in the i^{th} cell if and only if this point satisfies

$$(p_{ix} - q_x)^2 + (p_{iy} - q_y)^2 < (p_{jx} - q_x)^2 + (p_{jy} - q_y)^2$$

for all other predefined points j. These cells form the Voronoi diagram which is defined by edges and vertices. Since each cell presents the closest area to the predefined point, the points on edges are as far away from the predefined points as possible.

The number of predefined points under consideration will affect the number of vertices. A large number of predefined points will give a large number of vertices. This can be seen in Figure 2 which shows a Voronoi diagram with a rather tight grid for the Helsinki Harbor. The effect of what happens when the number of predefined points is decreased is seen in Figure 3, where only a subset of the predefined points are used. These predefined points are the corners of the harbor (marked as x_1 to x_6 in Figure 3) and were regarded as the most interesting with respect to the narrow passage and the final docking position. From these, the vertices (marked as v_1 to v_5) were obtained. Note that one vertex is not marked in Figure 3 because it is located far outside the map. Waypoints for navigation will then be defined on a set of edges in the diagram to the desired docking position, which is located between the predefined points $X20$ and $X21$.

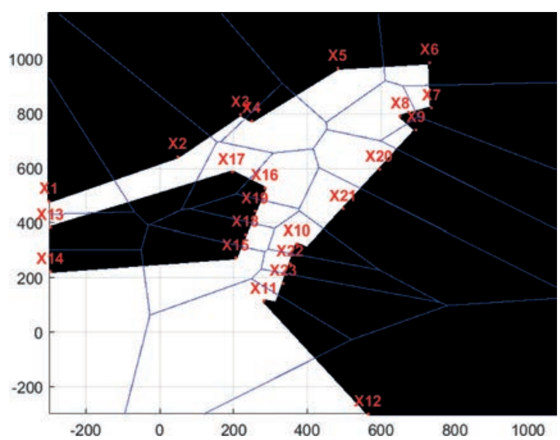

Figure 2: Voronoi diagram for the Harbor of Helsinki with tight grid

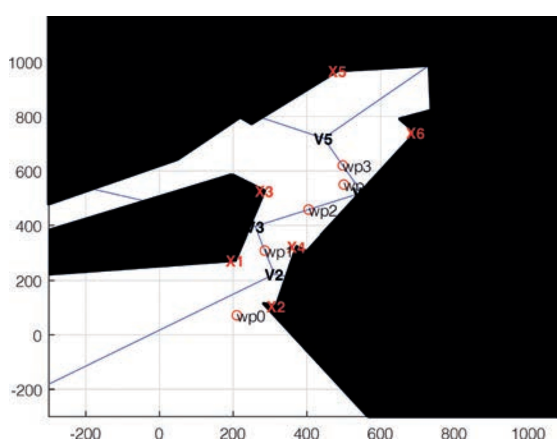

Figure 3: Voronoi diagram based on few predefined points

The chosen subset of vertices are then used to define waypoints that has a maximum distance to the bounds [24]. The waypoints are chosen as the middle points of two vertices in the Voronoi diagram, i.e. a waypoint is given by

$$P = (v_i + v_{i+1})/2 \qquad (10)$$

where it is the middle point for vertices i and i+1. The final docking destination is added as the last waypoint (wp4).

It is was chosen to use a Voronoi diagram with rather few points to get a limited number of waypoints. If there were many waypoints due to many predefined points, then it might be necessary to perform some kind of smoothing when the list of waypoints are used to generate the future reference for the MPC.

For each waypoint in the list, a desired yaw angle is also provided to allow the ship to navigate through narrow passages on its way to the final docking position. The yaw angle at a certain waypoint is determined from the average angle of the path between the preceding and the succeeding waypoint. The yaw angle for the docking position is given by the angle of the shore.

The guidance system keeps track of the current waypoint and once the ship approaches it, the GNC will start to shift the MPC's reference towards the next waypoint. The switch occurs when the following criteria are satisfied:

$$\begin{aligned} \sqrt{(X - X_{di})^2 + (Y - Y_{di})^2} &< \varepsilon_{1i} \\ |\psi - \psi_{di}| &< \varepsilon_{2i} \end{aligned} \qquad (11)$$

where X, Y and ψ are surge sway and yaw in earth frame, X_d, Y_d and ψ_d are desired surge, sway and yaw. Further, ε_{1i} and ε_{2i} are the allowed deviation for ith desired position. The procedure is outlined in Figure 4.

To give a smooth change in the reference to the MPC in the transition from one way point to the next, a timebased linear interpolation is used. This gives a gradually increasing position error which avoid pulses in the desired control actions.

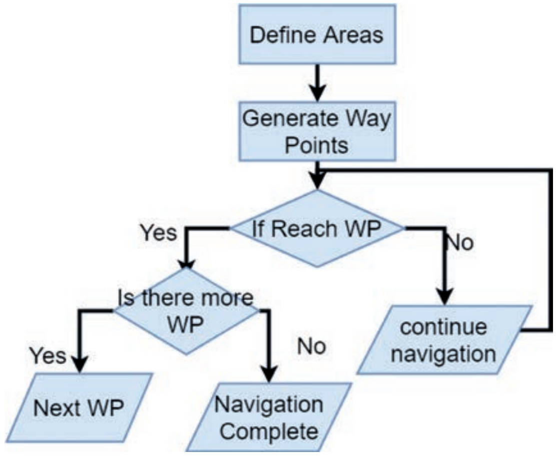

Figure 4: Guidance system function

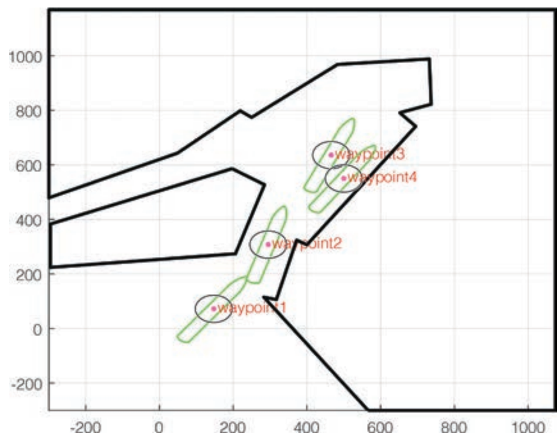

Figure 5: Waypoints for the automatic docking

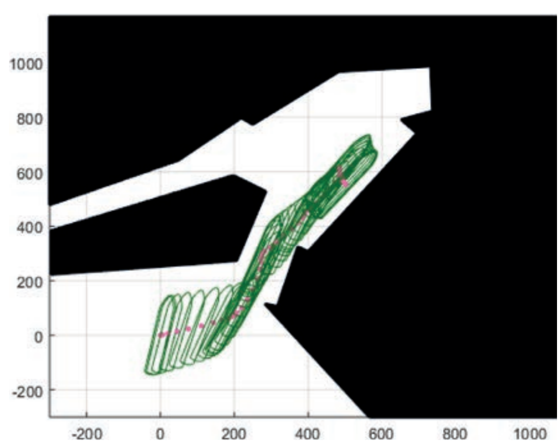

Figure 6: Positions and headings during the automatic docking

When (11) is satisfied, the new reference to the MPC is given by interpolating between the current and the next waypoint, i.e.

$$\begin{bmatrix} r_x \\ r_y \\ r_\psi \end{bmatrix} = \alpha(t) \begin{bmatrix} x_{\mathrm{wp}(i)} \\ y_{\mathrm{wp}(i)} \\ \psi_{\mathrm{wp}(i)} \end{bmatrix} + (1-\alpha(t)) \begin{bmatrix} x_{\mathrm{wp}(i+1)} \\ y_{\mathrm{wp}(i+1)} \\ \psi_{\mathrm{wp}(i+1)} \end{bmatrix} \tag{12}$$

where r_x, r_y and r_ψ are the position and heading references for the MPC, $x_{\mathrm{wp}(\cdot)}$, $y_{\mathrm{wp}(\cdot)}$ and $\psi_{\mathrm{wp}(\cdot)}$ are the waypoint positions and heading. The weighing factor is given by

$$\alpha(t) = \begin{cases} 1 & \text{if } t > t_b + t_0 \\ \frac{t-t_0}{t_b} & \text{if } t <= t_b + t_0 \end{cases} \tag{13}$$

where t0 is the time that (11) is satisfied and tb is the interpolation interval chosen by the user.

Note that the reference generation has intentionally been kept simple to focus on the concept of finding waypoint by using Voroni diagrams. This concept could be extended with an improved reference generation to get a smoother response from the system.

Control using MPC

The ship control system takes the vessel to the reference that is provided by the guidance system. MPC was chosen to explicitly handle constraints. Constraints are here mainly coming from limitations given by the harbor geometry and by obstacles. There are also limits given by the thrusters. All variables in the MPC are expressed in the linearized coordinate system.

It is assumed that the navigation system has the ability to filter out the influence of waves affecting the vessel and oscillating disturbances are thus neglected in the controller. To handle slowly varying environmental disturbances, e.g. current and wind, it is necessary to include integral action in the MPC. This also improves how the MPC is able to handle the mismatch between the model and the real world ship [25]. Integral action is introduced by using a model with the extended state vector

$$\bar{\boldsymbol{x}}(k) = \begin{bmatrix} \boldsymbol{\Delta x}^T(k) & \boldsymbol{x}^T(k) \end{bmatrix}^T \tag{14}$$

where $\boldsymbol{\Delta x}(k)$ are increments to the original state vector

$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{\eta}_p^T & \boldsymbol{\nu}^T & \boldsymbol{\tau}^T \end{bmatrix}^T \tag{15}$$

The extended discrete-time model is given by

$$\bar{\boldsymbol{x}}(k+1) = \bar{\boldsymbol{A}}\bar{\boldsymbol{x}}(k) + \bar{\boldsymbol{B}}_u \Delta \boldsymbol{u}(k) \tag{16a}$$
$$\boldsymbol{y}(k) = \bar{\boldsymbol{C}}\bar{\boldsymbol{x}}(k) \tag{16b}$$

where $\boldsymbol{y}(k)$ are the outputs, $\boldsymbol{\Delta u}(k)$ are the control signal increments, and

$$\bar{\boldsymbol{A}} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{0} \\ \boldsymbol{CA} & \boldsymbol{I} \end{bmatrix}, \bar{\boldsymbol{B}} = \begin{bmatrix} \boldsymbol{B} \\ \boldsymbol{CB} \end{bmatrix}, \bar{\boldsymbol{C}} = [\boldsymbol{0} \quad \boldsymbol{I}] \tag{17}$$

where $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are matrices in the discrete time representation of (9). Further, $\boldsymbol{C} = \boldsymbol{I}$ since all original states are assumed to be measurable.

By defining the error $\boldsymbol{e}(k) = \bar{\boldsymbol{C}}\bar{\boldsymbol{x}}(k) - \boldsymbol{r}(k)$ between the actual outputs and the desired set-point reference, the optimization in the MPC is

$$\begin{array}{rl} \min\limits_{\boldsymbol{\Delta u}(k)} & \sum_{k=1}^{N-1} \|\boldsymbol{e}(k)\|^2_{\boldsymbol{Q}_1} + \|\boldsymbol{\Delta u}(k-1)\|^2_{\boldsymbol{Q}_2} + \|\boldsymbol{e}(N)\|^2_{\boldsymbol{Q}_f} \\ & \bar{\boldsymbol{x}}(k+1) = \bar{\boldsymbol{A}}\boldsymbol{x}(k) + \bar{\boldsymbol{B}}\Delta\boldsymbol{u}(k) \\ & \boldsymbol{u}(k+1) = \boldsymbol{u}(k-1) + \Delta\boldsymbol{u}(k) \\ \text{s.t.} & \boldsymbol{y}_{\min}(k) \leq \bar{\boldsymbol{C}}\bar{\boldsymbol{x}}(k) \leq \boldsymbol{y}_{\max}(k) \quad k = 0, \ldots, N \\ & \boldsymbol{u}_{\min} \leq \boldsymbol{u}(k) \leq \boldsymbol{u}_{\max} \\ & \boldsymbol{\Delta u}_{\min} \leq \boldsymbol{\Delta u}(k) \leq \boldsymbol{\Delta u}_{\max} \end{array} \tag{18}$$

where $\|\boldsymbol{z}\|^2_{\boldsymbol{Q}} = \boldsymbol{z}^T\boldsymbol{Q}\boldsymbol{z}$. It penalizes deviations from setpoints via $\boldsymbol{Q}_1$, and increments in the control variables via $\boldsymbol{Q}_2$, i.e. the changed commanded forces and torque. It is also possible to have a penalty for the deviation of the final point in the horizon via $\boldsymbol{Q}_f$. Note also that the limits $\boldsymbol{y}_{\min}(k)$ and $\boldsymbol{y}_{\max}(k)$ may vary over the prediction horizon.
The MPC operates in the linearized coordinate system that at each sampling instant is aligned with the body-fixed system. Position measurements from the navigation system are in an Earth-fixed frame and velocity measurements are provided in a body-fixed frame. Hence, it is needed that references, geometrical limits of the harbor, and velocities are transformed into the current linearized coordinate system.

Positions are transformed into the linearized system using

$$\boldsymbol{z}_p = \boldsymbol{R}^T(\psi)(\boldsymbol{z} - \boldsymbol{o}_p) \tag{19}$$

where ψ is the yaw angle, $\boldsymbol{z}_p$ is the position of the vessel in the linearized frame, $\boldsymbol{z}$ is the position of the vessel in the Earth frame, and $\boldsymbol{o}_p$ is the position of the origin for the linearized frame in the Earth-fixed frame.

The initial state vector for the MPC in the linearized coordinate system is obtained in the following way:

$$\begin{array}{rcl} \boldsymbol{\eta}_p(k) & = & [0\ 0\ 0]^T \\ \boldsymbol{\Delta\eta}_p(k) & = & \boldsymbol{R}^T(\psi(k))(\boldsymbol{\eta}(k) - \boldsymbol{\eta}(k-1)) \\ \boldsymbol{\Delta\nu}(k) & = & \boldsymbol{\nu}(k) - \boldsymbol{R}^T(\psi(k))\boldsymbol{R}(\psi(k-1))\boldsymbol{\nu}(k-1) \end{array} \tag{20}$$

The states in the Earth frame needs to be stored from one sample to the next to be able to create the differential states. Note that linearized frame might have been rotated since previous sample, hence, the velocity $\boldsymbol{\nu}(k-1)$ has to be transformed to the current frame.

Results
The proposed method for automatic docking based on a combination of Voronoi diagrams and MPC are here demonstrated for a simulated ship.

The simulations were done in Matlab where the controller was implemented using the YALMIP toolbox [26]. A quadratic programming solver was used to solve the MPC problem. Constraints were expressed as soft constraints.

A 294 m long and 37.9 m wide cruising ship was used in the simulations. It is described by the 3DOF ship model in (8) where

$$\begin{array}{rcl} \boldsymbol{D}(\boldsymbol{\nu}) = \boldsymbol{D} & = & \text{diag}(4.32 \cdot 10^4, 2.67 \cdot 10^4, 2.2 \cdot 10^{10}) \\ \boldsymbol{M} & = & \text{diag}(4.62 \cdot 10^7, 6.77 \cdot 10^7, 2.54 \cdot 10^{11}) \end{array}$$

The simplified thruster model (6) is used with the same $T_{\text{thr}} = 10$ s for all actuators. This simple model is considered to be sufficient to demonstrate the auto-docking concept.

A discrete-time linearized model (16) was used in the MPC. The weights for the MPC problem in the loss function (18) are chosen as

$$\begin{array}{rcl} \boldsymbol{Q}_f & = & \text{diag}([10\ 10\ 10^9\ 5 \cdot 10^4\ 5 \cdot 10^4\ 0\ 10^4\ 10^4\ 0]) \\ \boldsymbol{Q}_2 & = & \text{diag}([1\ 1\ 10^7]) \\ \boldsymbol{Q}_1 & = & 0.1\boldsymbol{Q}_f \end{array}$$

where the weights $\boldsymbol{Q}_f$ and $\boldsymbol{Q}_1$ penalize deviations in surge, sway, yaw, surge speed, sway speed, yaw speed, surge force, sway force, and yaw torque. The weight $\boldsymbol{Q}_2$ penalizes changes in surge force, sway force, and yaw torque. The weights for the final point are chosen much larger than for the points for the transient behavior because the main objective is to reach the final point.

The sampling interval is 10 s and the prediction and the control horizons are both chosen to $N = 15$. The bounds for thruster forces $\boldsymbol{\tau}$ are chosen to

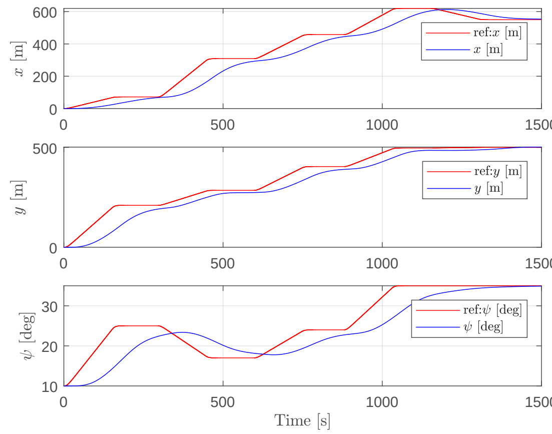

Figure 7: Positions in surge, sway and yaw in earth fixed system

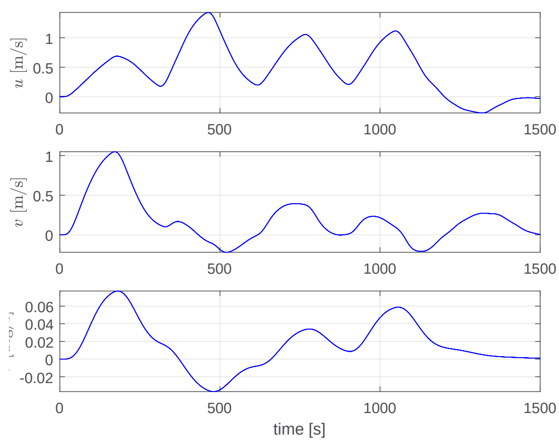

Figure 8: Velocities in surge, sway and yaw in body fixed system

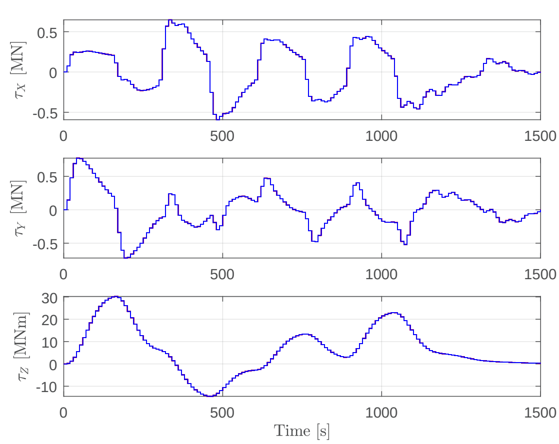

Figure 9: Forces and torque in body fixed system

be ±4 MN, ±0.9 MN, and ±50 MNm, respectively. Further, for all waypoints, the deviations in (11) are $\epsilon_{1i} = 20$ m and $\epsilon_{2i} = 10$ degrees, and the interval in (13) is $t_b = 150$ s.

From the Voronoi diagram in Figure 3 waypoints are created. The defined positions and headings are seen in Figure 5.

The whole automatic docking procedure is illustrated in Figure 6 where the ships position is drawn for selected samples during the docking. Here, it can be seen that the docking procedure manages to bring the vessel to dock without having any side of vessel hit any of the bounds from the harbor.

The positions of the ship in the Earth fixed system during the docking procedure are shown in Figure 7. The corresponding velocities in the body fixed system are shown in Figure 8 and the corresponding commanded forces and torques are shown in Figure 9. In Figure 7 it can bee seen that the ship's position is changed smoothly towards its docking position. It can also be noticed that the settling time for heading (yaw), ψ, is long, although it reaches the reference value at the end of the simulation. In total it takes around 1200 s for the vessel to reach its docking position with a sufficiently small error in the heading.

The main purpose of this study was to use Voronoi diagrams for the waypoint generation and use these in an MPC. Although the algorithm does its job fairly well there is room for improvements in how the transition from one waypoint to another is handled. A main reason for that is that the MPC is not using a trajectory of future references. To handle the transition as good as possible, the reference smoothing in (12) was introduced. Even with this smoothing is can be seen in Figure 8 that the surge speed of the ship decreases when the ship approaches a waypoint. The commanded forces and torques are seen in Figure 7. They show that the ship is gently docked with no excessive commands.

Conclusions

The main contribution of this paper is to propose a GNC system for autonomous docking and navigating of ships which combines Voronoi diagrams with model predictive control. A Voronoi diagram is used to generate a list of waypoints to be followed during the docking. An MPC is applied to control the vessel to follow set-points generated from the list of waypoints. The proposed ideas were demonstrated for a simulated autonomous docking in the South Harbor of Helsinki.

Future work will improve the set-point path generation for the MPC to avoid the decreased speed when intermediate waypoints are approached. Further, is is also of interest to do studies on minimizing the time or the needed fuel for docking. Another feature to include would be to dynamically regenerate the list of waypoints to avoid moving objects.

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