DIGITAL TWIN REPORT FOR DMA

Digital Twins for Blue Denmark

Danish Maritime Authority

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1 EXECUTIVE SUMMARY

Digitalisation has become a key enabler for making the maritime industries more innovative, efficient and fit for future operations. Increased use of advanced tools for designing and evaluating system performance, safety and structural integrity are generating a range of digital models of a vessel and its equipment. In the operational phase, cheaper sensors and increased connectivity together with increasing data storage and computational power are enablers for new ways of managing a vessel's safety and performance.

The maritime industry has many suppliers and stakeholders, and depends on efficient communication throughout the lifecycle of each vessel. The digital twin ship is a concept introduced to the maritime industry as a platform for efficient visualisation and exchange of all digital content generated for the asset. Digital twin thinking can be seen as an enabler for a more systemic approach in order to create value for all stakeholders in the industry.

The digital twin will integrate data from many different sources including analytical models, information models, 3D visualisation, system models including automation systems and networks, and sensor data. A digital twin gives the possibility to exchange information, system data and analysis results through a platform for information management and collaboration, where the experts can work together to prevent costly mistakes and rework. Access to sensor data, remote monitoring and analytics made possible by the digital twin enable more profitable, safe and sustainable operations.

As modern ship systems become more complex and integrated, optimal performance depends on all sub-systems to work optimally, both individually and aggregated. It is challenging to have a full overview of these systems, but at the same time essential for designers, system integrators and operators to have a deeper understanding of how systems interact and how their choices and actions affect the overall system performance and robustness.

A prerequisite for system integration and cooperation is a wider use of standards and development of new standards, e.g. covering formats for data, communication, models and interfaces.

A digital twin can be the perfect tool to build this common understanding as it facilitates:

- Exchange of all relevant ship information, data, analyses and models, updated to reflect close to real-time status of all systems on board each ship.
- A collaboration platform for design and simulation across system boundaries.
- Controlled sharing of data, models and updated asset information between stakeholders.

It is believed that Blue Denmark can benefit significantly from systemising future digitalisation efforts on a digital twin platform. Some benefits for selected stakeholders are;

- For **ship owners**, digital twins will provide a tool for visualisation of ship and subsystems, qualification and analytics of operational data, optimisation of ship performance, improved internal and external communication, safe handling of increased levels of autonomy and safe decommissioning.
- For **equipment manufacturers**, the digital twin will provide a tool to facilitate system integration, demonstrate technology performance, perform system quality assurance and promote additional services for monitoring and maintenance.

- For **authorities**, the digital twin will offer a systematic framework that can be set up with applications to feed live information and generate required reports from each ship. This can ensure higher quality reporting on critical issues without putting extra burdens on crew.
- For **universities**, the digital twin offers a new platform on which to increase system understanding and facilitate knowledge exchange enhancing research and development and education in a range of technological disciplines.
- For **maritime academies**, the digital twin can act as a platform for training that can increase each candidate's understanding of the whole ship and train them in systems thinking to see the integrated consequences of actions taken.
- Digital twins will require specialised **consultancy services**. Their role will be to accelerate efficient generation of the digital twin concept, e.g. with regard to state-of-the art requirements and standards for model exchange and handling of large scale data.

Central to the digital twin concept is the creation of a digital asset ecosystem, or an asset management platform. The digital asset ecosystem will be a network of interconnecting and interacting data, software and hardware models relating to the asset and its systems, hereby avoiding operating in silos. One powerful aspect of this approach is enabling a new generation of advanced predictive analytics that are central to improve future ship performance management.

There is great potential for the digital twin models in demonstrating that technologies and processes, e.g. on emissions, comply with international and national standards and regulations, as well as industry standards. Furthermore, they can provide technical assurance of new or modified technologies.

In creating platforms for digital twins where simulation models, vessel documentation and operational data can be shared and analysed, the maritime industry will have a powerful instrument supporting design, production, operation, retrofits, upgrades and decommissioning of both individual ships and fleets. Creating a platform for testing new designs and operational changes on continuously updated vessel information will allow a more systemic thinking in Blue Denmark. The consequences of changes will be possible to assess both for designers and operators facilitating more optimal and integrated designs.

2 INTRODUCTION

Shipping is undergoing a transformation where operations increasingly are relying on digitalisation to optimise profit and verify compliance to regulatory and customer demands, as described further in /1 and /2. Digitalisation in the maritime industry is essential to maintain control of revenue streams and minimise the environmental footprint. Recent developments have the potential of changing incentives and business models across the value chain, from design to production, operations and decommissioning.

Many digitalisation initiatives are already live and maturing; some rely heavily on use of operational data and some focus more on automating vessel documentation and reporting to increase fleet efficiency. There is also a large potential in making the ship design, construction and commissioning phases more efficient through digital tools that enhance collaboration and system integration at an early stage. The digital twin ship is a concept introduced to the maritime industry covering all the mentioned aspects. Digital twin thinking can be seen as an enabler for a more systemic approach in order to create value for all stakeholders in the shipping industry throughout the lifecycle of each ship in the fleet.

It has long been the case that asset operators have not made, or in many instances have not been able to make, full use of available digital information and tools. With the current set-up in shipping it is difficult to make large investments without immediate pay-back. Management and organisations should take up the challenge and make a stepwise approach towards taking full advantage of these new opportunities.

From an organisational point of view, shipping is diversified with outsourcing of technical management and manning and differences in ownership structures. In this respect, the digital twin approach with an underlying IT platform can enhance efficiency throughout the organisation.

This report will describe potential advantages of having a framework for digital twins available to all stakeholders of Blue Denmark, encouraging collaborative efforts towards an efficient digital future.

2.1 Digital twin definition

A digital twin can be defined as a digital representation of a physical asset, its related processes, systems and information. Digital twins combine state-of-the-art engineering models and analytics with asset specific operational data to create digital simulation models and information models that are updated and changed throughout the lifecycle of their physical counterparts. A digital twin continuously learns and updates itself through sensor data that measure various operational aspects, through input from experts with relevant industry knowledge, using data from similar assets, and from interaction with the environment.

The digital twin models will be constructed prior to and in parallel with the actual building of a vessel. As illustrated in Figure 1, software models will support feasibility studies of early design and virtual commissioning, and facilitate system integration testing prior to and during the construction and building phase. In operation, the digital twin becomes a system for continuous integration, processing and analysis of sensor data describing its performance and integrity. Performance data and simulation models can indicate possible changes to design or operation that can provide increased efficiency or life extension for a vessel. For decommissioning the digital twin can be an information platform systemising documentation of materials used, and hereby support proper handling of environmental and labour safety issues.

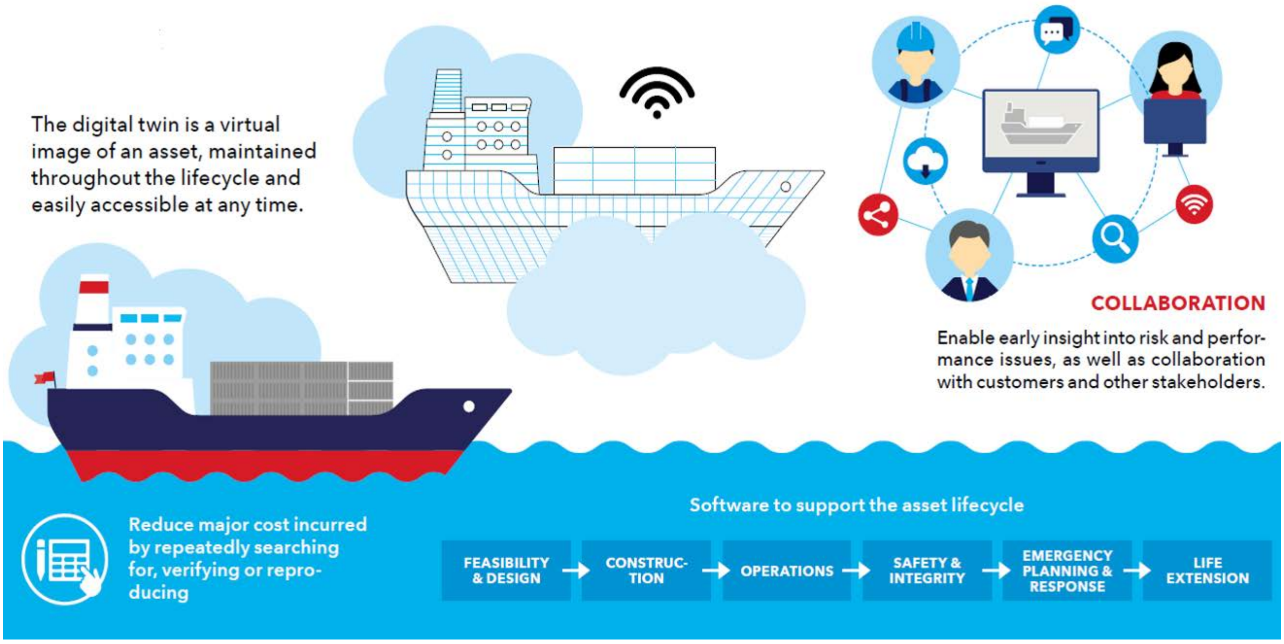

Figure 1 The digital twin as a tool to support vessels throughout the lifecycle

2.2 Digital twins – bringing experts together

The digital twin is a concept that will enhance information management and collaboration, where experts can work together, preventing costly mistakes and rework. A digital twin can enable:

- A cloud-based platform solution where all relevant ship data, analyses and models are available at any time – both for individual ships and the entire fleet.
- Information updated real-time throughout the lifecycle of a ship, from design phase to decommissioning.
- Analytical and time-domain simulation models updated and refined with operational data and sensor data to closely reflect the real assets performance.
- Bringing in and storing external operation specific data such as weather, current and waves.
- A collaboration platform that prevents stakeholders form working in silos.
- Controlled sharing of data, models and updated asset information between stakeholders.
- Early insight into potential design conflicts.
- Improved quality and efficiency of approval and certification processes, e.g. through replacing periodical surveys with condition and event based inspections.

Exchanging information between many different suppliers and stakeholders has always been essential for the maritime industry, see Figure 2. As modern ship systems become more complex and integrated, optimal performance depends on all sub-systems to work optimally, both individually and aggregated. It is challenging to have a full overview of these systems, but at the same time essential for designers, system integrators and operators to have a deeper understanding of how systems interact and how their choices and actions affect the overall performance.

A digital twin can be the perfect tool to build this common understanding.

Figure 2 Digital twins for exchanging information between stakeholders

Industrial assets are designed, built and operated by engineers who rely on many different data sources, various models and work with enormous amounts of data. Specialized teams create models separately, conducting analyses for their specific tasks. This way of working means that the most current information and calculations may not be readily available for crucial decisions, because the teams operate in silos. It drives cost and inefficiencies, creates uncertainties and represents a vast amount of time and resources.

Central to the digital twin concept is the creation of a digital asset ecosystem, or an asset management platform. The digital asset ecosystem must be a network of interconnecting and interacting data, software and hardware models relating to the asset and its systems, hereby avoiding operating in silos. One powerful aspect of this approach is enabling a new generation of advanced predictive analytics that are central to improve asset performance management, /5.

The digital twin will integrate data from many different software products with the possibility to exchange data and results, through a platform for information management and collaboration, where the experts can work together, preventing costly mistakes and rework. Sensor data, remote monitoring and analytics made possible by the digital twin enable more profitable, safe and sustainable operations.

3 BACKGROUND

3.1 Enabling technologies

Digital technologies have been available and utilized in the maritime and other industries for decades. However, recent developments have made the uptake of digital solutions accelerate rapidly. Below are some developments that have made this ongoing digitalisation journey possible across many industries, and which leads us to believe that digitalisation will be essential to optimize operations also in the maritime industry:

- Cheaper sensors:

  Smaller and cheaper sensors make large volumes of data available from a range of components, overall systems and the environment /7.

- Increased connectivity:

  The “Internet of Things” and “Industrial Internet of Things” allows systems and components to connect, exchange and act upon information from each other (“inner” connectivity). This enables a whole new level of automation of systems and decision processes on-board a vessel, /6.

  Improved satellite technology allows for larger volume and higher frequency data transfer (“outer” connectivity). A careful selection of information and data to transfer, the measurement frequency of each data point and type of communication system to use should be done to minimize the costs. More details on ship connectivity can be found in /8.

  Efficient on-board communication and ship to shore communication also opens for advances in remote diagnostics and condition based maintenance.

- Cloud computing:

  Recent developments in cloud computing have made scalable and cost-efficient data processing and data storage accessible from servers available through the internet. Services for storage and protection of large scale data and efficient access to large scale computational power are available for any industry to access and further develop to fit their needs.

  This development has encouraged platform solutions for cooperation between multiple stakeholders in the maritime industry. One example is the Maritime Connectivity Platform (MCP). MCP is a communication framework enabling efficient, secure, reliable and seamless electronic information exchange between all authorized maritime stakeholders across available communication systems, /9. Another concept is the Veracity platform from DNV GL, developed for stakeholders to analyse, control and share operational data from the maritime industry, /10.

- Data analytics:

  The falling prices of processing power and storage space have made them affordable to more stakeholders. In addition, innovations in software, algorithms and statistical methods have been developed or implemented as free software. These two factors have significantly lowered the material cost of analysing data, and have effectively made the necessary tools available to anyone with the skills and will to deploy them, /6.

- Artificial Intelligence including machine learning:

  AI and machine learning are increasingly used to introduce «smart systems» that are trained based on large amounts of data. These systems can be used in a wide range of contexts from image recognition to complex control algorithms. Digital twin simulation models can be applied to train and verify such algorithms.

- Automation and autonomy:

  Efficient algorithms for remote controlled and self-controlled components and operations are developed and tested in increasing numbers in a range of industries. The maritime industry has seen this development from unmanned machinery space to (near) future concepts for unmanned and autonomous vessels. Digital twin vessels will be essential to understand, train, certify and maintain such autonomous systems, where large-scale simulations of complex operational scenarios will be needed.

- Improved simulator technology:

  Development of algorithms for large-scale co-simulation of complex systems allows for simulating complex phenomena across different physical domains.

Given the technology advancements described above, new areas need development to allow the different industry stakeholders to take full advantage of concepts like the digital twin. Standardisation of models and interfaces, sensor naming and references, and sensor quality and reliability are some key factors that are discussed further in /7.

3.2 Digital twin applications

Even though the concept of digital twins has existed for several decades, only recent developments as described above have made it possible to realize an in-depth system simulation of a complete asset such as a ship, including physical models, as well as cyber physical systems (systems controlled and monitored by computer-based algorithms).

The US Air Force and many car manufacturers, such as Maserati, have used digital twins to reduce cost and time in design, sourcing of equipment and components, and manufacturing and operation. Equipment manufacturers, like General Electrics (GE), are increasingly relying on them in their core business processes for example for wind farms.

In the maritime business, digital twins have recently been adapted as a concept and tested for various technical domains. As illustrated in Figure 3, a multitude of asset properties and data can be embedded in a ship's digital twin model:

- Analytical models for structures and hydrodynamics are important as design tools, for verification of designs and for performance optimisation.
- Information models for systems and components are important to assure proper operation and maintenance, safety assurance and reporting to authorities.
- 3D visualisation models can be applied for vessel design, operational planning and training.
- Time-domain models of components and systems provide basis for process optimisation, control system testing, operational planning and training.
- Sensor and process data from the real vessel is used for performance monitoring, condition based maintenance and for decision support.
- Software driven control algorithms and virtualised communication networks are used for testing and verification of software updates, and for virtual operations.

The pilot applications so far represent separate elements seen in the lower part of Figure 3. Current developments are focusing on making the proper platform for connecting the elements in an overall digital twin ecosystem. This work is essential to allow each of the stakeholders in the business to obtain maximum benefit from all the information contained in a digital twin.

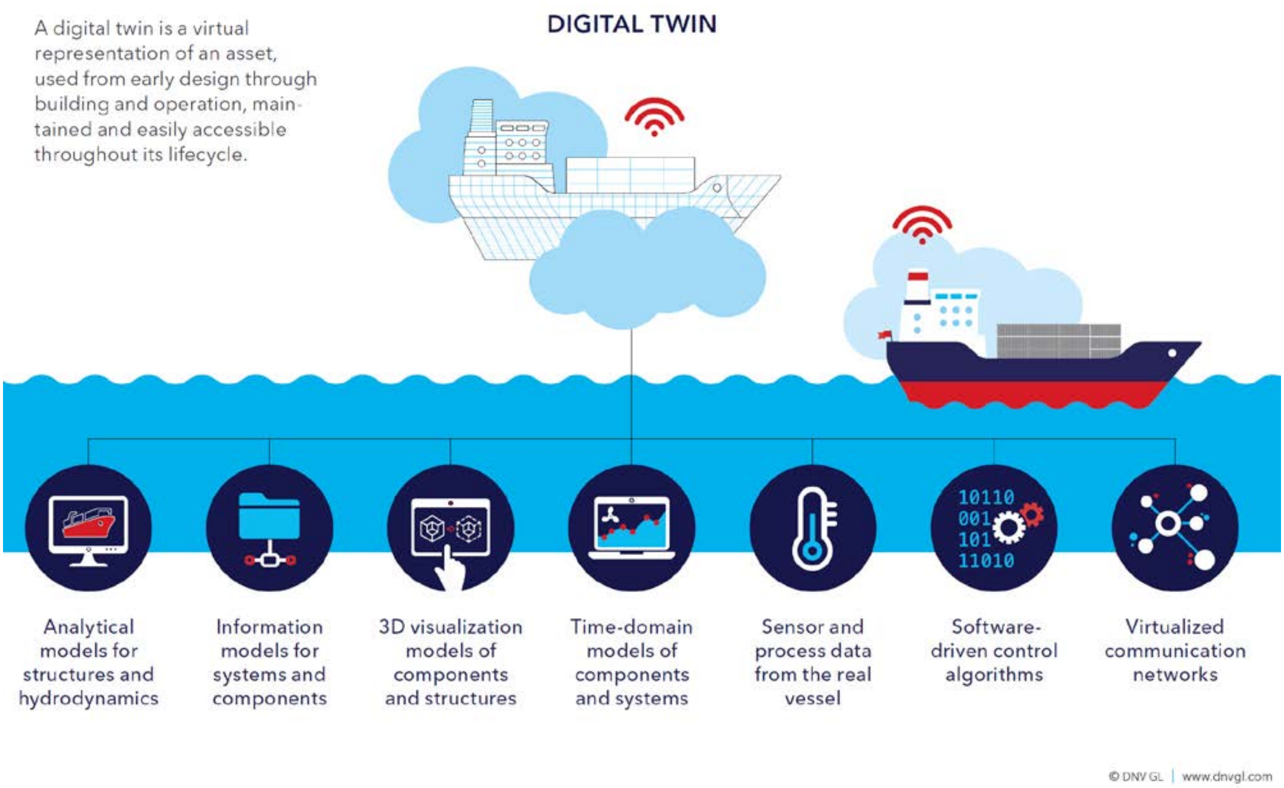

Figure 3 Elements of a digital twin ship, /3.

As an example, deviations between live sensor data and associated digital twin model data can indicate events that require action, e.g. fatigue in a structure, maintenance need on a component, a faulty sensor that should be overridden or changed, or unwanted changes to the vessel's systems and software. The latter could e.g. indicate an unscheduled software update/patch that is affecting the vessel systems, a new physical component introduced on the network, or malicious cyber-attacks on networks and systems.

There is great potential for the digital twin models in demonstrating that technologies and processes, e.g. on emissions, comply with international and national standards and regulations, as well as industry standards. Furthermore, they can provide technical assurance of new or modified technologies.

4 CREATING VALUE FROM DIGITAL TWINS

Many of the stakeholders in the maritime industry already have methods and tools that can be seen as digital twins supporting their products and services. The natural next step is to combine and integrate these tools into the context of a digital twin ship, and thereby maximise the benefits and value creation for the industry. This section describes examples of how value can be created for a range of stakeholders in the maritime business[1].

4.1 Ship owners

As ship technology is mature, optimised operations are a key to maintain positive revenues in the future of shipping. More systematic use of operational data can provide an in-depth knowledge of vessel performance and real-time control of the fleet costs.

On-board systems are installed with an increased level of automation and autonomy, ranging from remote control through various levels of automatic control to fully self-controlled. Digital twin simulation models can be used to demonstrate, train and test/verify/certify such systems. This is essential for safe introduction of these systems that can potentially give large savings in operational costs, both due to increased crew competence level and reduced manning.

For ship owners, digital twins of their assets will provide a tool for 1) visualisation of ship and subsystems 2) qualification and analytics of operational data, 3) optimisation of ship performance, 4) improved internal and external communication, 5) safe handling of increased levels of autonomy and 6) safe decommissioning. The tools can provide decision support throughout all levels of the organisation. Being continuously updated through a vessels lifecycle, the digital twin can ultimately provide insight into all factors affecting operational performance.

For sake of simplicity the term ship owner is used here catering for all functions in relation to the ship and its crew. However, shipping takes advantage of outsourcing and out-shoring in relation to operation, technical management, and crewing etc. The digital twin must allow these suppliers easy access to relevant data and models and at the same time take position on the overall responsibility for the efficiency of the ship.

4.1.1 Visualisation of ships and subsystems

Updated 3D models for static visualisation of the state of components and vessel, and for dynamic visualisation of historic, real-time and predicted future operations can act as a powerful tool to investigate initial designs and potential changes in operations. With such visualisations, opportunities and potential conflicts are easier to uncover and explain for all stakeholders of a system.

Visualisation tools can assist in preparing crew for changes to an operation, and provide the opportunity to test such changes in a controlled virtual environment. This way, communication and cooperation between ship-crew and land based personnel can be facilitated.

4.1.2 Data qualification and analytics

Both static and time-domain models give important input for selecting relevant data to be measured for performance monitoring or reliability based maintenance of a component or system. The digital twin can simulate operations that generate data to feed applications during development. This can train applications for future analytics and qualify the measurement set-up in terms of required number of measurement points, sensor range, reporting frequency and data quality.

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[1] Annex A. EXAMPLES OF DNV GL DIGITAL TWIN APPLICATIONS FOR MARITIME gives more concrete examples on applications of the digital twin approach

During operations, digital twins can be used to identify faulty measurements (e.g. sensor drift or failure). Deviations between live sensor data and associated digital twin model data can indicate events that require action. Also, values not easily measured can be simulated based on a digital twin model fed by continuous measurements that through known physical relations and/or data analytics can provide the desired output variables.

4.1.3 Optimisation of performance

The structured collection of and access to operational data offered by a digital twin can be used to identify possible improvements to the operation. Some areas for potential improvements that can be visualised/calculated by a digital twin are:

- Optimal operation of machinery systems.
- Optimal retrofit of batteries, more efficient thrusters, bulb etc.
- Performing hull or propeller cleaning.
- Verify ship performance on a detailed level. Visualise the effect of design choices and changes.
- Benchmarking performance towards other vessels in the fleet.

Overall, digital twins can be used for visualising and calculating performance of different design choices prior to major retrofits and conversions.

From a fleet point of view the digital twins for the different ships can contribute to assuring optimal allocation of resources between vessels in giving decision support to what vessel will benefit the most from potential upgrades.

4.1.4 Internal and external communication

A digital twin for a vessel can facilitate common ship and system understanding for crew and the land based organisation. This can improve the communication between them and play an important role in establishing a company culture that seeks optimisation in all operations.

Using a model based framework for communication and reporting can mitigate the risk of not having employees with required competence in all areas. Crew on other vessels or employees on land can assist in identifying potential threats/failures in a system and train less skilled employees to mitigate events and perform correct repair.

Digital twins should support reporting systems that request each point of input only once to a central information model that can generate the specific reports required both for internal stakeholders and for relevant authorities and verification bodies. This can reduce the crew's reporting workload and have a positive impact on reporting quality through avoiding redundant documentation and managing complex reporting requirements in a more automated way.

4.1.5 Autonomous operations

Remote operation and more autonomous components have gradually been introduced on board. The trend now is a development towards making larger more complex system operations, and even the overall ship, fully autonomous. In this context, adapting the digital twin technology for testing and verification of systems can be of high value for assuring safe and efficient operations.

4.1.6 Decommissioning

The systematic registration of hull structures, materials (including hazardous) and equipment will create a good basis for optimal decommissioning processes catering for the highest value of the ship, environment and safe and sound labour conditions.

4.2 Equipment manufacturers

For equipment manufacturers, the OEMs (Original Equipment Manufacturers) will be responsible for interacting with the digital twin platform per specifications from the owner. It is important for the OEMs to bring in sub suppliers in efficient innovation processes aiming at development of components and systems. This demands that the OEMs are able to set up collaborations respecting the digital twin platform.

The digital twin platform will provide a tool to 1) facilitate system integration, 2) demonstrate technology performance, 3) perform system quality assurance and 4) promote additional services for monitoring and maintenance. Through development of standardised model interfaces and proper collaboration platforms, component models and system information can be shared without revealing intellectual property.

4.2.1 System integration

OEMs have to integrate their component and system specific simulation models in an overall digital twin simulation platform with interfaces to other OEMs. Hereby it is possible to demonstrate performance and functionalities of a complex system prior to commissioning of new systems or for retrofit of new components in existing systems.

The overall simulation platform contains a library of standardised components, serving as reference models to build up a generic vessel environment relevant for testing. Vessel specific models can be supplied as nearly self-contained components where only a minimum of information needs to be shared between the models, enabling a highly modular approach where varying model fidelity levels are used depending on the application. An illustrative example of such a collaboration platform is further described in Appendix A 1.

Proper system integration at design stage can reduce required commissioning time when installing new components. Software updates are typical upgrades to a system that can be tested prior to deployment, reducing the risk for the manufacturer of causing down-time for on board systems.

4.2.2 Performance

Simulation models with the ability to demonstrate performance of components and systems can be developed by mathematical models and be verified and improved by component specific operational data. Such models can be delivered during innovation and design phase to assure proper component selection and be included in the digital twin to support system and component assessment throughout the vessel lifecycle.

4.2.3 System quality assurance

For OEMs and their sub-suppliers there is a necessity for tools to efficiently generate simulation models of their assets that, given the proper format and system interface, can be integrated in a digital twin simulation platform. Such models can be used for internal system quality assurance through model based testing, from design of components, to project specific applications and throughout operation. Employing a digital twin framework, modifications and upgrades to a component or system can be tested on up-to-date models and verified through operational data before they are installed on the real vessel.

4.2.4 Additional services

The larger manufacturers, especially OEMs, are offering integrated services along with their products in terms of systems for remote monitoring and analytics to predict future performance or service needs (CBM – Condition Based Maintenance). The adaption of digital twins in the industry will increase the value of such systems.

Ship designers and owners can get added value from installing new advanced services offered by the OEMs through integrating these services on a digital twin platform for optimal design and operation of integrated systems.

As noted above, a prerequisite for efficient generation of digital twins will be that OEM manufacturers comply with standards for proper model development and interfaces. They will also need to deliver quality assured data streams from their components and systems. Such standards are yet to be developed for several of the areas that can potentially be covered by digital twins.

To simultaneously protect OEM IPR and enable necessary sharing of information between stakeholders, it will be necessary to incorporate proper frameworks for data ownership, model ownership and verification of black-box models. As system complexity and the level of autonomy increase, and the exposure of individual OEMs and their business risk increases correspondingly, it will also be essential to build trust in the integrity of the ship as a complete system. This means that any unauthorized changes to ship systems must be detected and dealt with. In this context, block chain technology combined with the digital twin of the ship may hold the answer.

Furthermore, the digital twin can play an important role in new business models such as power-by-the-hour, where manufacturers maintain control of products throughout their lifecycle, reducing investments or operational cost for their customers and assuring longer life-time with less maintenance need.

4.3 Authorities

For authorities, the digital twin will offer a systematic framework that can be set up with applications to automatically feed information and generate required reports from each vessel. This can ensure higher quality reporting with fewer burdens on the crew, and enable an increased transparency throughout the value chain.

Live vessel information (AIS data) about position and destination is already available online, for relevant authorities these services could be expanded to contain information about for example crew, cargo, certificates, class status and green passports. This information could be exploited for more efficient port state control.

Looked at from a Flag State point of view applications generating information on e.g. safety, navigation, environment and labour issues can be used for targeting critical issues for the respective ship. In the same way, live data from operation can be used for emission control. Similar considerations can be included into Port State Control regimes.

For class and vetting the same observations can be applied. Furthermore, the digital twin can be developed to serve as design verification by authorities and class, an example can be found in annex A 3.

The EU project Efficiensea2 (http://efficiensea2.org/) investigates a related concept of having automated flow of information related to port calls. The idea is to provide digital information about the port, and to have a portal for uploading of all information needed from the ship. If all such portals are enabled to take in a data file of specified format, the digital twin on the ship side can generate this file with only limited action from the crew on-board. Furthermore, this can be a first step in preparing for the arrival of autonomous vessels into ports.

Such opportunities require that certificates for both the vessel and crew are available in digital format and continuously updated to satisfy reporting requirements. Portals for digital submission, retrieval and renewal of certificates already exist for some providers of class, statutory and crew certificates.

More advanced applications can also be made available based on live vessel data. Recently the Norwegian Coastal Administration has taken a tool into operation that produces live accident risk models for traffic in national waters.

4.4 Universities

For universities, the digital twin offers a new platform on which to build research and education. Instead of everyone starting from scratch and working in silos, it is possible to build on the past and current work of others and in a more efficient manner accelerate innovation and development. This can be realized through a digital twin presenting multiple domains on a common digital platform, and hereby increase system understanding and facilitate knowledge exchange enhancing 1) research and development and 2) education in a range of technological disciplines.

4.4.1 Research and development

Universities and research institutes are using modelling and simulation to demonstrate new concepts and designs for ships and sub-systems. Standardisation of model development and interface requirements can facilitate the exchange and reusability of models between researchers and with relevant companies and knowledge sharing with the industry to drive technology development further.

Well proven digital twins with large amounts of operational data for existing vessels will be of high value when developing and testing methods and algorithms for remotely controlled and autonomous applications.

4.4.2 Education

Representing multiple domains and visualising performance of vessels, sub-systems and operations makes the digital twin a good tool for communication in education and towards the general public.

The increased use of programming, simulators and algorithms for data analytics in education will prepare the candidates for contributing to modern industry development. Simulation platforms and generic models, combined with facilitated access to operational data to calibrate and understand the models, can significantly improve the system understanding of new candidates.

4.5 Maritime academies

Training of future and existing maritime personnel is essential to increase the uptake of digital solutions in shipping.

Maritime academies can explore the digital twin concept through offering training in adapting this virtual representation of the asset for decision support. Academies can link to vessels in operation, and future employees can investigate live-streamed data through augmented reality, visualise historic data and simulate scenarios to test results of operational changes. Such training can increase the understanding of the whole vessel and train them in systems thinking to see the integrated consequences of an action.

4.6 Consultancies

Digital twins will require specialised consultancy services. Their role will be to accelerate efficient generation of the digital twin concept, e.g. with regard to state-of-the art requirements and standards for model exchange and handling of large scale data.

There will be need for supporting the industry with:

- Modelling competence within disciplines such as hydrodynamics, structures, process optimisation, machinery performance, control systems and logistics.
- Data management: What and where to store data? How frequent to update data? How to assure sufficient and secure back-up.
- Visualisation: 3D visualisation of static and dynamic models. Presenting business intelligence data and data analytics in an accessible way.
- Making applications: With a standardised framework for model and data exchange a range of generic applications for analytics and visualisations can be developed and offered to clients.

The need for consultancy services depends on the competences within the shipping companies and suppliers of equipment. The size of the companies as well as the business model with outsourcing and out-shoring will be decisive for the need.

5 SYSTEMIC THINKING IN THE MARITIME CLUSTER

In creating platforms for digital twins where simulation models, vessel documentation and operational data can be shared and analysed, the maritime industry will have a powerful instrument supporting design, production, operation, retrofits, upgrades and decommissioning of both individual ships and fleets.

The digital twins will be accessible to all stakeholders in the value chain supporting the ship throughout its lifetime. Creating a platform for testing new designs and operational changes on continuously updated vessel information will allow a more systemic thinking in Blue Denmark. The consequences of changes will be possible to assess both for designers and operators facilitating more optimal and integrated designs.

5.1 Prerequisites for successful introduction of digital twins

To gain full advantage of introducing common digital platforms some important factors must be in place:

- Competence development:

  Existing employees, both ship based and land based need training to benefit from the new tools. New categories of ship based as well as land based employees are required.

- Organisational changes:

  New ways of organizing work through the whole value chain will be required, at the ship as well as in land based organisations. More integrated processes for ship design and operational planning will be enabled, and organisations must reflect this.

- New business models:

  For several stakeholders, new business models can be introduced. Examples are equipment manufacturers leasing out products, and systems and consultancies delivering platform services or applications.

  Furthermore, the digital twin aims for more efficiency in outsourcing and out-shoring of shipping functions.

- Standardisation:

  Standardisation is an important enabler for digitalisation. For digital twins, standards on e.g. vessel documentation, model interfaces, data quality, sensor naming and user interfaces are a few areas that will require exchangeable formats.

- Public acceptance:

  Several factors will require public acceptance. Ships operating with less crew or even fully autonomous need to demonstrate significantly higher safety levels than existing ships. Increased sharing of data about assets and crew needs to be justified not only from an efficiency point of view, but also from assuring safer and more sustainable operations of the fleet.

Processes are already on-going to address the above-mentioned prerequisites. Learning from other industries and developing the services through an agile process with frequent feedback from all relevant stakeholders in the maritime industry is essential to assure successful platforms for digital twins.

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A. EXAMPLES OF DNV GL DIGITAL TWIN APPLICATIONS FOR MARITIME

A 1. Digital twin for system integration, testing and optimisation

The DNV GL digital twin concept for system testing and integration has its origin in technology developed for Hardware-In-the-Loop (HIL) testing of control system software. Figure 4 shows a generic sketch of a control system in normal operation, with control signals connected to actuators on the system under control and feedback signals from sensors. The control system consists of dedicated control system hardware (e.g. programmable logic controller (PLC's), controllers, human-machine interface (HMI's), networks) and control system software. For regular HIL testing, the real system under control is replaced by a HIL simulator that includes models of the actuators, dynamics and sensors, as well as the operating environment. The control system should not detect any difference between controlling the real system, and interacting with the HIL simulator. This enables extensive testing of software functionality, robustness and performance in a virtual and risk-free environment, in parallel to the vessel construction timeline.

In a digital twin framework one will virtualise the entire test setup, /3. The control system software is now running on emulated and virtualised hardware, which means that the entire test setup consists only of software, see Figure 5. Note that the control system software by nature is digital, and therefore is included in the test setup unchanged. This new software entity has become a digital twin component.

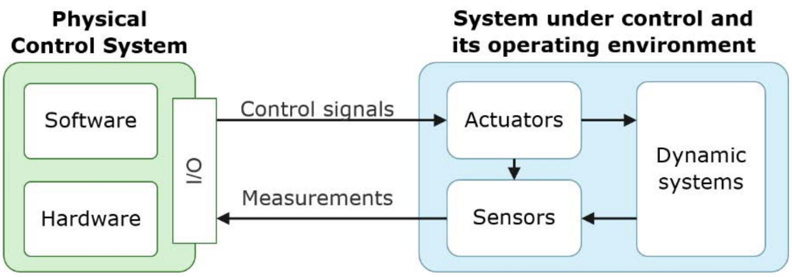

Figure 4 Control system in normal operation

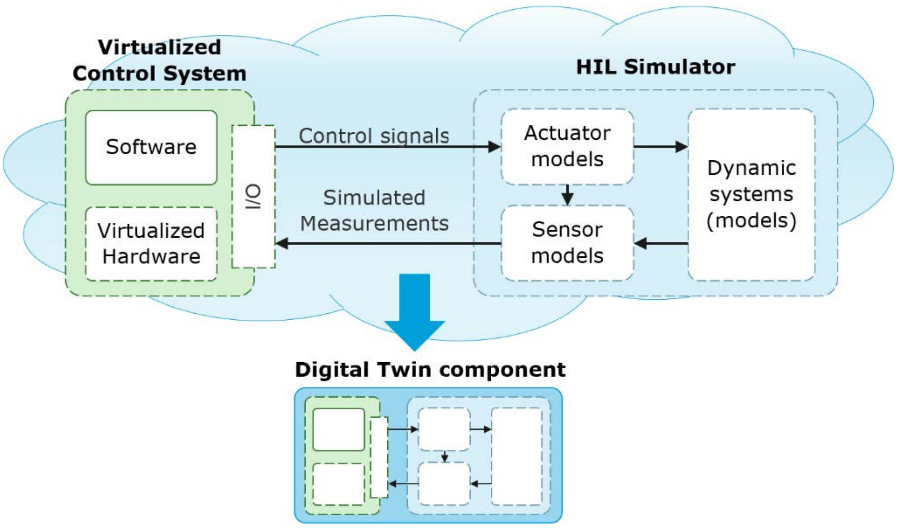

Figure 5 Virtualised control system and hardware

With the digital twin components, available as runnable executables with well-defined interfaces, they can be assembled into a complete digital twin vessel. The DNV GL digital twin concept consists of simulation models for components and systems that have loose couplings, meaning that they can be supplied as nearly self-contained models where only a minimum of information needs to be shared between the models. Furthermore, the simulations take a co-simulation approach, which means that there is no centralized equation solver. Instead, each model has its own solver and the simulation core engine (master algorithm) orchestrates the communication between the models, see Figure 6. It involves reading the outputs and setting the inputs of the simulation models in addition to stepping model time.

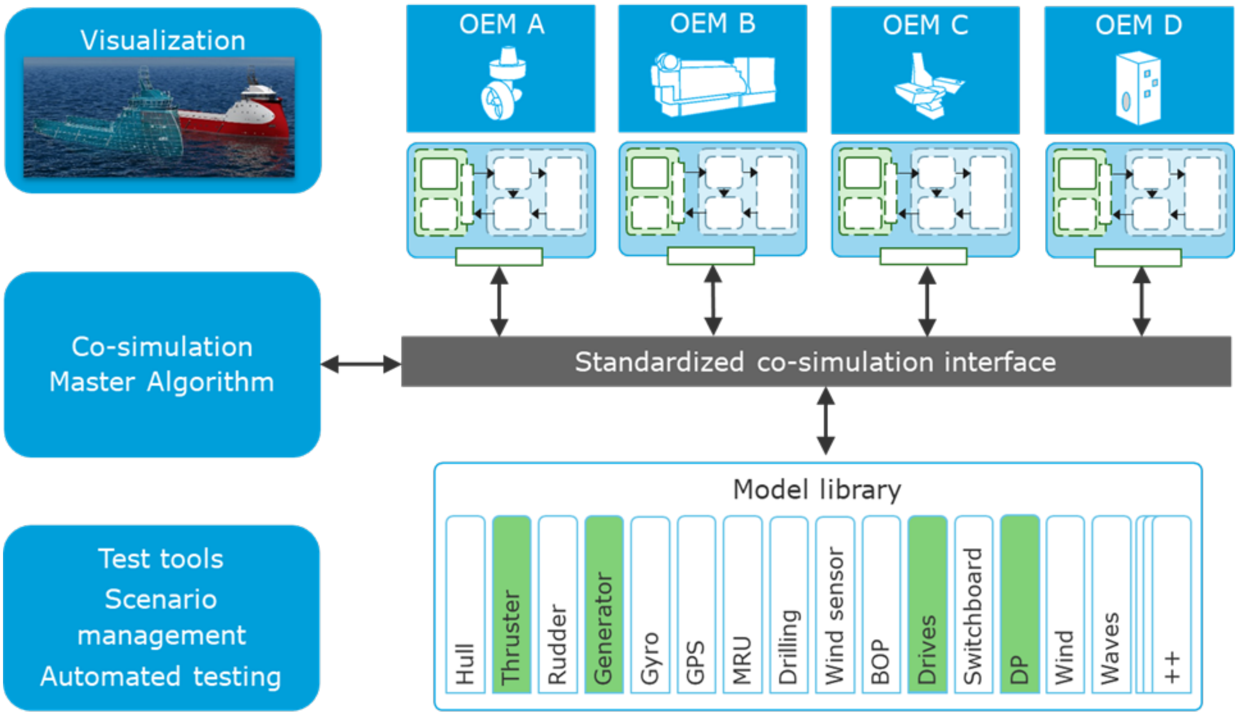

Figure 6 Digital twin platform for testing of system integration, see /3 and /4 for details

A library of DNV GL reference models is available and can be utilized to model parts of the vessel in combination with models provided by the designers and equipment manufacturers. When contributing to building the digital twin vessel by providing digital twins of their systems, manufacturers can explore how their systems interact with the complete vessel. The yard will have a preview of the real commissioning and can gain early insight into potential conflicts, resulting in fewer errors and less need for on board modifications.

A 2. "Nerves of steel"

Nerves of steel is a DNV GL innovation project to investigate new ways for calculating the damage risk from waves on a ship hull in a precise manner. Accurate descriptions of historical weather conditions for a specific vessel can be obtained by matching ship position data with historical wave data. By combining such data sources with a model for wave loading and response, we can calculate damage risk from waves on a ship hull given a more realistic estimate of the experienced load.

The prototype is based on generic models for a range of ship types. For ships where data sets from hull sensor monitoring are available together with detailed hull models one will be able to predict the experienced fatigue loads, extreme loads and seakeeping for vessels in a more accurate manner giving continuously updated models of the hull state. As the illustration in Figure 7

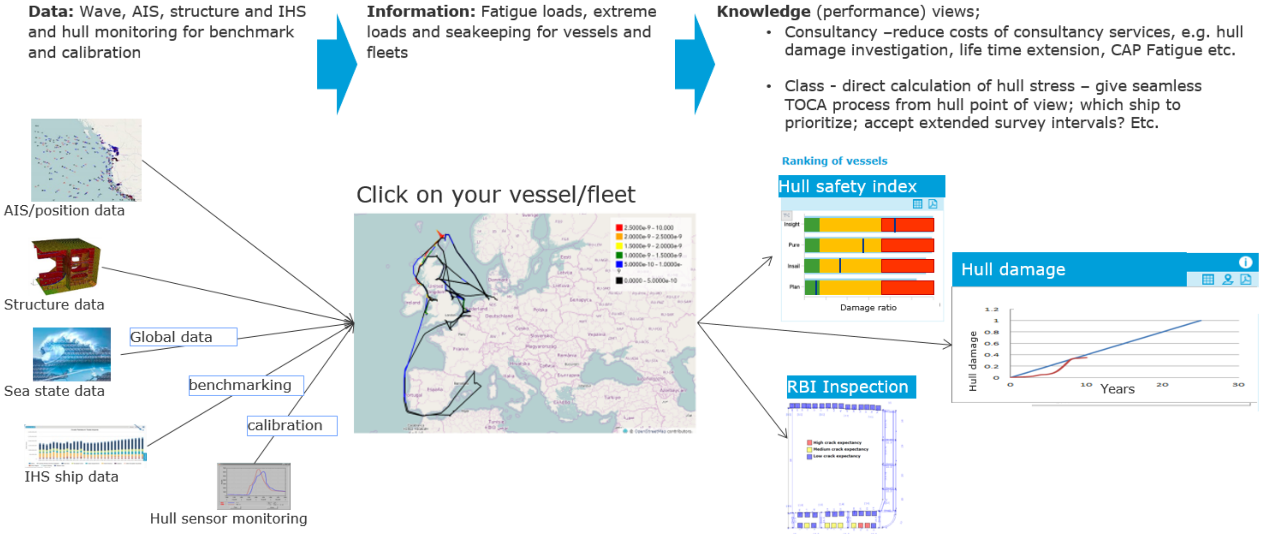

Figure 7 Calculating damage risk from waves

A 3. Approval

DNV GL has run pilot projects with customers to prototype, test and evaluate technology and work processes which eliminate the need for exchanging 2D drawings for the purpose of design verification by Class. This approach will need a prototype infrastructure for digital model sharing, model storing and versioning as well as model verification and approval. The model sharing and storing should be strongly integrated into a future digital twin framework.

The "Approved" project has revealed that there are ongoing consolidations of technology within software where many small custom solutions becomes few high-volume solutions, also for the ship designers. Consequently, the cost of technology decreases as it is shared over a large number of users, and it is thus believed that making more standardised interfaces for approval will be affordable.

The joint project aims to establish a fully digital workflow for seamless digital model exchange between stakeholders during the basic design process in ship newbuilding. In addition, the concept of a 3D digital information model will also be explored for other design disciplines and has potential to be used in the operational phase of the vessel.

Sharing models and visualisation of design simulation will be a cloud based service fitting well with a digital twin framework. One of the most important outcomes of above pilots is an approach towards industry standards for digital exchange formats and content of digital design models.

A 4. Verify algorithms for condition based maintenance, CBM

Reliability of a system can be improved through Condition Based Maintenance (CBM) by close monitoring of possible failure mechanisms and taking decisive actions to avoid the development of failure mechanisms through operational measures in the short-term and through maintenance in the long-term. The failure mechanisms may therefore not be able to develop, leading to the avoidance of a potential breakdown of the component or system. Diagnostics and prognostics algorithms for implementing a condition monitoring system are based on one of two main approaches: a model-based (first principles physical model) approach or a data-driven (statistical and data-mining) approach as illustrated in Figure 8, see /11 for further details.

For model-based approaches valuable insights into failure modes can be obtained through simulations of the system, by integrating material-level, component level and system-level models, and these may also be used to estimate how the component and system performance is affected by degradation. Based on comparison of the simulation and the actual measurements from the physical component, it may be possible to diagnose the component. This approach does not require large amounts of previous failure data to identify an imminent failure, and therefore may be most suitable for newly developed equipment with good computer models and limited failure statistics.

The data-driven approach utilizes previous failure data and correlates measured condition data with known failures using pattern recognition techniques like clustering and neural networks. One substantial advantage compared with the model-based approach is that there is less need for detailed physical knowledge of the monitored components. However, detailed statistics and measurements related to previous failures are necessary, and therefore this approach may be most suitable for legacy equipment with good statistical data on failures, with no need for developing a model of the physics. A disadvantage compared with physical model-based approaches is that the statistical models assume an underlying stability in the monitored system. Changes in load conditions or operating profiles may lead to inaccuracies because historical data is relied upon to diagnose a fault.

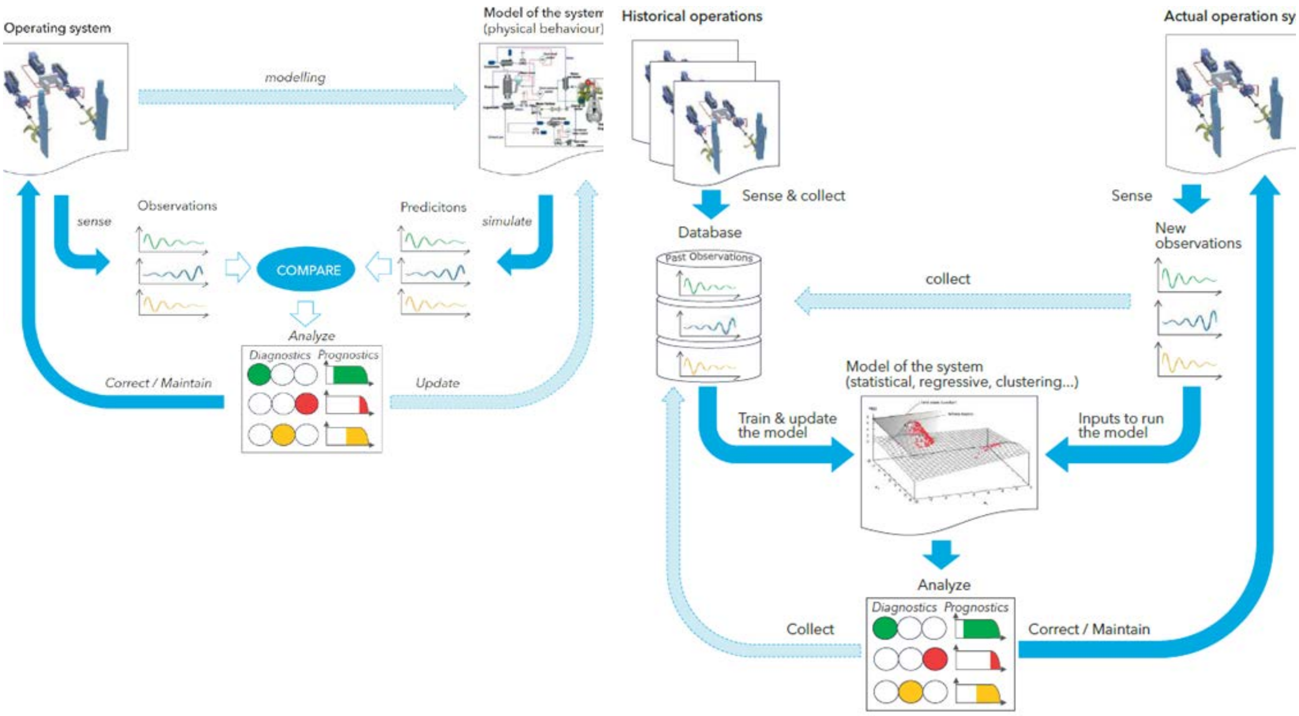

Figure 8 Model-based vs data-driven approach for Condition Based Maintenance, /11

Recent offshore classification rules for DNV GL open for predictive maintenance schemes to be approved by class, allowing for extension between survey intervals. For a vessel owner and class to trust the validity of the new maintenance schemes and algorithms for predicting behaviour and detecting failures there are several approaches to assure quality of underlying algorithms. Figure 9 illustrates how generic digital twins can be adapted to tune or verify algorithms that predict vessel and sub-system performance.

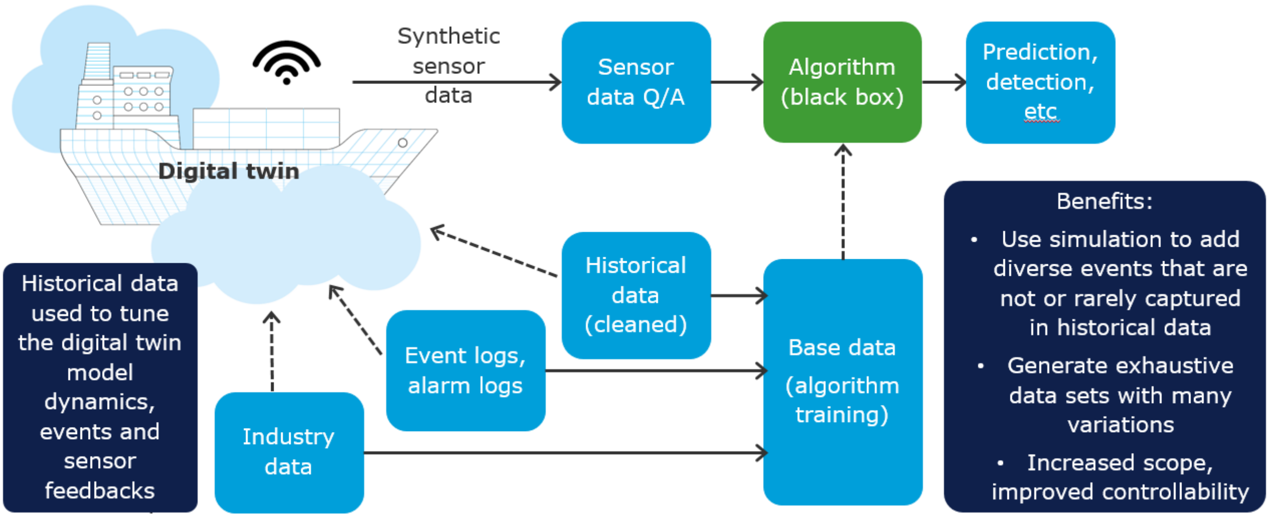

Figure 9 Digital twins for tuning of black box prediction algorithms

The largest cost element of running a traditional CBM program is the annual cost of analysing data, identifying alarm conditions and initiating maintenance activities. With increased use of condition monitoring systems, reduction of time to assess equipment in safe condition, more efficient reporting and "economy of scale" the cost per ship for running a CBM program can be significantly reduced. There is clearly a potential for increasing efficiencies of a CBM program through digitalisation and digital twins.

A 5. Risk models

'Probabilistic Twin' has been launched by DNV GL as an extension of the Digital Twin concept, while the latter is a digital copy of the physical asset, the probabilistic twin is a forecasting tool to support effective risk management in operations, coupling the digital twin to risk models which are continuously updated based on actual conditions and new knowledge. Preliminary work on coupling risk models with data analytics has already been carried out.

A 6. Veracity

DNV GL is currently developing an open industry data platform enabling the sharing of data, algorithms and transactions between industry assets. With industry-wide data sets, DNV GL aims to unlock data silos and provide a frictionless, quality-assured data market place that truly releases value. The platform is open in the sense that it will profile and quality assess data, allowing customers either to perform their own analytics or invite others, including DNV GL, to perform analytics on their assured data (www.veracity.com). With this collaborative data platform, the trust that DNV GL has established over decades advising clients and managing joint innovation projects is critical.

What DNV GL has learned from running dozens of big data projects with customers over the last year is that it is not a quick fix to address these challenges. There is no magic switch. That is also why DNV GL is developing Veracity together with selected leading industry partners and learning from this "private preview" phase to develop a robust data platform for general availability for the entire industry later.

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil & gas and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our professionals are dedicated to helping our customers make the world safer, smarter and greener.