**PAPER • OPEN ACCESS**

# On Risk of Digital Twin Implementation in Marine Industry: Learning from Aviation Industry

View the article online for updates and enhancements.

# **IOP ebooks**™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

# On Risk of Digital Twin Implementation in Marine Industry: Learning from Aviation Industry

**Michaela Ibrion[1], Nicola Paltrinieri[1], Amir R. Nejad[2]**

[1]Mechanical and Industrial Engineering Department, Norwegian University of Science & Technology, NO-7491, Trondheim, Norway
[2]Marine Technology Department, Norwegian University of Science & Technology, NO-7491, Trondheim, Norway

E-mail: `Michaela.Ibrion@ntnu.no`

**Abstract.**   This paper presents some aspects of the risk and challenges associated with digital twin implementation in the marine industry by learning from the aviation industry where the digital twin is more widely employed. The digital twin applications in aviation and marine industries are presented and the main steps of developing a digital twin are discussed. The three main steps of sensors (measurements), model, and data analysis are identified and used in the study. The lessons from two recent accidents in the aviation industry (Boeing 737 MAX crashes in Indonesia and Ethiopia in 2018 and 2019) are studied in details and discussed. It was found that the sensor reliability, model failure and wrong decisions as the output of the data processing are among the risks associated with digital twin implementations. In particular, from the case study accidents, it was found that the digital twin may not be able to represent all the possible scenarios which a system may experience in its life time. The digital twin presents many advantages, however the implementation of the digital twin is associated with risk and high uncertainties, even in the industries like the aviation industry, where the digital twin is well established and at a higher advanced level than in the marine industry.

## 1. Introduction
Digitalization is becoming an integral part of the engineering arena, and an interesting technology which aspires to move industries forward is the digital twin. In terms of historical roots of the digital twin term, it seems that Michael Grieves from the University of Michigan was the first to write and use the digital twin term, back in 2002. Nevertheless, the National Aeronautics and Space Administration (NASA) was using the term and applied the concept of "pairing technology" which is a predecessor of the digital twin technology, since the beginning of space explorations [1].

Nowadays, the digital twin is appreciated to become a key for digital transformations of many industries. The digital twin becomes so increasingly popular, as it is seen to drive many innovative solutions and to increase performance and profitability.

With regards to the aviation industry, Dennis Muilenburg, the Boeing CEO, mentioned in his speech at the panel discussion in Morgan Stanley Laguna Conference – California, on 12 September 2018 – that the digital twins usage for component production has increased the quality of parts and systems used in aircraft production by 40 percentage. Muilenburg highlighted that because of digital twin usage "We are seeing things like 40 to 50 percentage

improvements in first time quality". Boeing is looking further to reduce development costs and to create new alternatives for supply chains. Digital twin makes real-time updates accessible by all users, enables virtual system integration and test, reduce development costs and the risk of design problems. As per Muilenburg "That digital life cycle – think of it as a digital twin of our airplanes – will unleash incredible value in the future" [2]. Furthermore, Canaday [3] emphasized about the increasing role of the digital twin in the aircraft health monitoring. The digital twin is estimated that will improve the maintenance and can bring an estimated 30 percentage improvement in cycle time for critical processes. According to Domone [4], by using a digital twin, engineers can more accurately determine the life of structural components for aircraft. Digital twin contribute to improve performance, to generate savings and to increase operational flexibility [4].

In terms of investments to the digital twin's implementation, Domone [4] advised that the digital twin can definitely offer improvements for the civil aircraft fleet life management, but an important consideration in usage of digital twin is given by the cost-to-benefit ratio. A low–fidelity digital twin approach which incorporates measures operational weight for civil aircraft operations is associated with relatively low cost and has the potential to extend life for asset. On the other hand, a high–fidelity geometric approach is of a high interest, but it is not providing much benefits, as it is associated with high–costs. A low fidelity approach digital twin is bringing a good value with reference to cost versus benefits, as it contributes to optimize operations and fleet usage. This type of digital twin is already in–use by engine manufacturers in civil aerospace. A high-fidelity digital twin can add knowledge about detailed component geometry, mechanical assemblies, system calibration details and can updates these through the collected data over the asset's life. A high-fidelity digital twin has the potential to increase component fatigue life, but with present technology and cost, it requires huge amount of data and particularly, high investment costs [4].

Digital twin is seen as a definitive technological trend in the marine industry. Primarily, the digital twin offers the contribution that an asset is monitored in operational conditions and the data is digitally represented in virtually real-time [5]. Moreover, there are many more to be offered by digital twin; the digital twin allows to perform virtual tests, to reduce time in physical tests, can improve design, allows failing and to check errors before manufacturing process, and decreases the price for manufacturing and development time. The digitalization and particularly, usage of the digital twin, has the potential to increase efficiency of the Condition Based Maintenance (CBM) through reduction of time to assess equipment, assures a more efficient reporting, increases usage of condition monitoring systems, and reduces the cost for running CBM [6]. Furthermore, DNV GL has developed a methodology for hull condition monitoring that incorporates the usage of the ship's digital twin, a virtual model prepared during the design stage. Combined with waves, position and sensor monitoring, the digital twin usage enhances the value of predictive and preventive maintenance. Moreover, it was seen that a combination between data provided by sensors and digital twin extends considerably structural details accessible for monitoring and makes more accurate the condition monitoring of a vessel or other offshore structures and assure a cost-effective instrumentation [7].

DNV-GL emphasized that digital twin can reduce the cost over the operation phase, can contribute to safety and integrity and adequate preparedness and planning can be done with regards to emergency response and planning. Digital twin can indicate possible changes to design and operation and can contribute to efficiency and life extension of an asset. In terms of decommissioning, the digital twin can support labor safety issues and environmental matters [6].

The application of digital twin in marine industry is not limited to vessels, but offshore renewable technologies can also take advantage of digital twin [8]. As per Johansen [9], the offshore wind turbine market is growing and many maintenance and downtime issues are linked

to drivetrains, more precisely to bearings. This matter, in addition to remote and rough offshore environments poses challenges for maintenance and elevates the costs for operation and maintenance. The development of digital twin can be a solution to these challenges. For instance, the modelling of a digital twin for drivetrain in a Multi-Body Simulation (MBS) software requires attention and further investigations. However, creating a high-fidelity digital twin model in offshore wind energy is an issue still to be settled. For the wind farms, the digital technology together with data science, industry expertise and a condition monitoring system can enable outcomes such as automated detection of early gear damage, in time inspections and repairs, reduction of downtime, and reduction of operational costs [10]. Johansen and Nejad [8] emphasized that a digital twin is highly relevant, particularly, for the condition monitoring of marine drivetrains and machinery, the holistic condition monitoring and predictive health monitoring of an asset. Moreover, when considering difficult to access and high values assets in offshore wind industry and shipping, the digital twin implementation can contribute in decreasing maintenance costs and downtime.

Despite many benefits that the digital twin can offer, less is written about the challenges linked with implementing the digital twin. Johansen and Nejad [8] through the case study of Wilhelmsen Ship Management Norway, brought to attention that when the shift from offline Condition-Monitoring (CM) to online CM will occur and cost challenges linked to sensors and their connectivity will be solved, then progress will be done towards implementation of the digital twin as the future of ship operations. However, the need to bring further to attention the challenges associated with digital twin implementation still requires further studies which is the main objective of this article.

## 2. Research approach

The aim of this paper is to identify and analyse the sources of risk associated with building and implementation of a digital twin in marine industry by learning from aviation industry which is an industry where the digital twin concept has been well established. With reference to the building and implementation of a digital twin, Johansen and Nejad [8] identified common steps among the industries. Essentially, three steps are the key points of a digital twin development: sensors, model, and the Remaining Useful Life (RUL), fault prediction, and operational decision making, see Figure 1.

The first step of digital twin development refers to sensors which come with their own challenges in terms of high failure, reliability, calibration, efficient and optimized placement and proper selections, just to name a few [8].

The second step for building a digital twin refers to model development. The question which may raise here is which type of model is needed in digital twin development. In order to analyze the data from sensors, in general, there are two approaches: physical-based modeling (PBM) and data-driven modeling (DDM) approaches. The PBM is built up based on real physics of the system, for instance utilizes the equation of motion to predict the system behaviour. The DDM is a model which is built based on data features like for example, after collection of data, it considers the correlations with certain faults or it is evaluating the trend, without relating to physics of the system. This type of model requires collection of large amount of data [8].

The third step considers the output from a model which needs to be analyzed for the RUL and fault prediction. Further on, data interpretations and validations are performed, and recommendations are given for the system performance [8].

The case studies of two recent disasters in aviation industry were analyzed through the above mentioned steps in order to identify critical factors and risk in the implementation of digital twin in aviation industry. The marine industry needs to learn from the aviation industry which is well-known as an advanced industry with reference to the building and implementation of digital twin [2, 3, 4].
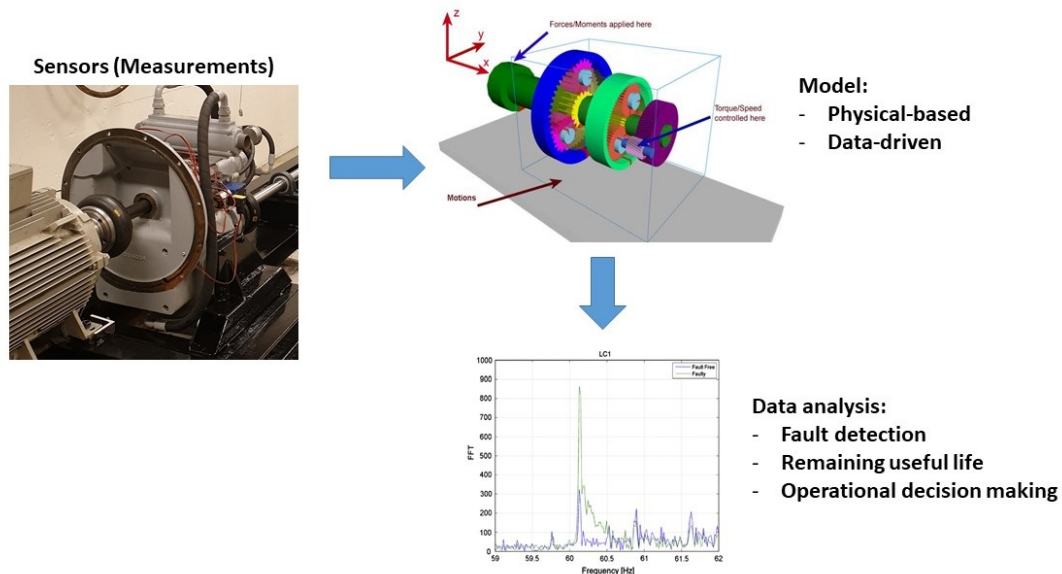
**Figure 1.** Digital twin main steps.

## 3. Digital twin in aviation and marine industries

Digital twin signifies basically a virtual representation of the system containing all information available on site. According to Marr [1] the digital twin is a virtual model of a product or process, and acts as a bridge between the physical and digital world. The origins of the digital twin term can be traced back in 2002, at University of Michigan when Michael Grieves introduced it during a presentation to industry as part of the Product Lifecycle Management (PLM) center and during first executives PLM courses. As per Michael Grieves a digital twin has always existed before a physical product comes to existence. A digital twin is seen as a virtual image which contains all the information of a physical product and reflects it throughout the whole product lifecycle. This means that there is a mirroring or twinning of physical and virtual systems, and the conceptual model was called initially as Mirrored Spaces Model or Information Mirroring Model [1, 11].

A digital twin as presented by General Electric is "a dynamic digital representation of an industrial asset, that enables better understanding and prediction of the performance of machines". Each asset can have its own digital twin and operational details can be accessed throughout its life [4]. Erikstad [12] warned that the digital twin is not an end product in itself. Furthermore, the interpretation of digital twin concept can varies according to different stakeholders and industries. Within the followings, insights about the digital twin in aviation industry and marine industry are introduced.

### 3.1. Digital Twin and Aviation Industry

Through the digital twin a virtual replication of physical airplane parts is provided by usage of simulation software. The virtual model of highly complex systems and components, such as those featured on the Boeing's airplanes are subject to simulations about the lifecycle of the environments and conditions that component(s) or systems might experience [2]. The digital twin can bring improvements in structural life prediction and can enable better management of an aircraft over its service life [13]. The Boeing started to embrace the digital twin concept from 2017, and the digital twin was launched through an official letter called the Innovation Quarterly.

The digital twin or the model based-engineering was used to design the Air Data Reference Function (ADRF) for the 777X. The ADRF is a key avionics function which process signals from pressure and temperature probes, computing aircraft state parameters like airspeed and altitude, processes signals and data, convert the physical information about flight environment into digital information on cockpit displays for usage by pilots. It was assessed that the digital twin contributed to reduce the cost and time in order to develop the ADRF on the 777X Boeing [2].

A digital twin in aviation has been explained as being the virtual replica of a physical asset, like for example, an aircraft engine, which can display to engineers on the ground how the engine is running while the aircraft is still in the air. A question has emerged about how the health monitoring through a digital twin differs from a traditional health monitoring. The answer is that the digital twin applies the monitoring approach much earlier, deeper and in more detail, tracks and monitors an asset in real-time taking in account for instance, the temperature of engine, pressure and airflow rate. In this way, through a digital twin and through a virtual model of aircraft, major systems and components, early warnings and predictions of the components behavior and possible likely failure can be received, identified and consequently, action plans can be built. For instance, GE developed the first digital twin for an airplane's landing gear, and sensors were placed on typical failure points such as hydraulic pressure and brake temperature in order to provide real-time data. This helped to predict the early malfunctions and to diagnose the remaining lifecycle of the airplane landing gear. Data gathered by sensors on the asset are compared with data from its digital twin; simulations are going on about the regular wear and tear and environmental conditions, for instance. In case the two data sets do not match up, then, actions are being taken and asset can enter into service [3].

*3.2. Digital Twin and Marine Industry*
Erikstad [12] identified five characteristics of the digital twin in maritime industry: identity, representation, state, behavior and context. However, there is no universal acceptance of these characteristics which might be neither required, nor sufficient.

DNV-GL [6] defined the digital twin as a "digital representation of a physical asset, its related processes, systems and information". Furthermore, DNV-GL [6] advised that a digital twin is constructed prior to and in parallel with the actual building of a vessel. The digital twin is a tool which can support for instance, a vessel, over its life-cycle [14]. The digital twin can support the feasibility stage, early design, prior to and during construction phase and commissioning. During the operation of an asset, a continuous learning and updating occurs with reference to the digital twin of asset which receives various data about operational aspects, environmental data, data provided by sensors and input from experts with a relevant industry knowledge [6]. Furthermore, the digital twins facilitates exchanging information among stakeholders such as owners, manufacturers, operators, service providers, system integrator, authorities and different suppliers. A common understanding and exchange of information can be done through various ways such as a cloud-based platform which offers access to operational data, data from environmental conditions such as weather, current waves, sensors data, analysis and analytical and time-domain simulation models [6]. In 2018, as an example, a group of students from the Marine Technology Department, NTNU has developed a digital twin of NTNU's research vessel Gunnerus in collaboration with DNV-GL. The work on digital twin has continued further developing a method for the RUL calculation of thruster and it will be integrated into the digital twin platform.

According to Bekker [5], the digital twin is "digital, real-time, in-context, operational mime of an asset, which connects the digital and real world representations". For instance, the polar supply and research ship SA Agulhas II from South Africa can contribute high value to marine industry if the digital twin technology is best implemented. It was found out that a successful

implementation of the digital twin will depend on technology readiness, cost of implementation, associated requirements in terms of accuracy, quality and time resolution. Moreover, digital twin allows the measurements and analysis of extreme operational loading like experiments were performed in an operational laboratory [5].

Tian [15] applied digital twin for monitoring and maintaining marine systems such as propulsion systems. The parameters of a test rig from the Lab of Marine Systems Dynamics and Vibration, Department of Marine Technology, NTNU were used to build a physical based digital twin; the tool of Ansys Twin Builder was employed for building the model.

With regards to the offshore wind industry, GE [10] emphasized that through a constant collection of data about environmental conditions, component information, service reports, performance of similar models in the GE (General Electric) fleet, a predictive digital wind model is being built. In Trondheim, Norway, the Fedem Technology (SAP SE) has developed a digital twin and applied it to several systems, like for instance to offshore wind turbines.

## 4. Learning from failures in aviation: Boeing 737 MAX crashes in 2018 & 2019

The Boeing's current in-production models include the newest and top selling models such as 737 MAX, 777X and 787. The Boeing 737 Max series represent the latest model within the Boeing's 737 line and comprise the Max 7, 8, 9 and 10 models. The 737 has been very successful line for Boeing, but the Boeing 737 Max has been the fastest-selling in the Boeing's history, as around 100 different operators around the world ordered together more than 4500 Boeing 737 Max. Boeing launched the 737 Max on 30 August 2011, and the first 737 Max was rolled-out of factory in December 2015. This model have been in commercial usage since 2017, when the Malaysia-based Malindo Air received the first delivery on 17 May 2017. Since 2017, Boeing had delivered 350 pieces of the Boeing 737 Max 8 model by the end of January 2019. A small number of Boeing's Max 9s are also operating around the world, and the Max 7 and 10 models, are not yet delivered, but are due for roll-out within the next years [16, 17].

However, the Boeing 737 Max which has been the best-sold aircraft in the world, has come under intense scrutiny by 2018. Within a period of 6 months, two deadly Boeing 737 MAX accidents took place, one in 2018, and another in 2019. The two disasters occurred shortly after take-off during the critical climb phase. The first disaster crashed the Lion Air Flight 610 into the Java Sea, 12 minutes after taking off from Jakarta, in Indonesia, on 29 October 2018. The second disaster occurred six months later, on 10 March 2019, and the Ethiopian Airlines Flight 302 crashed six minutes after take off from Addis Ababa, Ethiopia [16, 17].

After the crash of the Ethiopian Airlines Flight ET302 on 12 March 2019, the national aviation authorities and airlines around the world have grounded the Boeing 737 MAX 8 due to big safety concerns. At the the time of crash in Ethiopia, more than 350 airplanes of the 737 MAX 8 were in operation around the world. The biggest operator in the world for the Boeing 737 MAX is the Southwest Airlines in the US. However, the United States was one of the last countries to ground this model of airplane. Globally, the China Southern Airlines is also one of the biggest Boeing 737 MAX 8 operators, and among the Europe's largest operators are the Norwegian Airlines, the TUI Airways and the Ryanair. Turkish Airlines is considered also as a big operator of this model.

### 4.1. Lion Air Flight 610 crash in 2018, Indonesia

The Lion Air Flight JT 610 Boeing 737 Max 8 took off from Jakarta on Monaday, 29 October 2018, at 06.20 (23.20) with destination of city Pangkal Pinang. After 13 minutes, it crashed and all his 189 passengers and crew were killed. By the time it crashed, this Boeing had only 800 hours of flight time [18].

After the Lion Air crash, it was found that the aircraft had experienced problems with a sensor which calculates the angle of flight, or angle of attack. The Digital Fly Data Recorder (DFDR)

of the airplane recorded a difference between left and right AOA (Angle of Attack) of about 20 degrees. Moreover, data recovered from the cockpit voice recorders has revealed that pilots were searching for a way to fix the aircraft's nose of pitching down because of the faulty AOA sensors. Furthermore, pilots were struggling to deal with an automated safety system – known as the Manoeuvring Characteristics Augmentation System (MCAS). Practically, the pilots were constantly fighting against the MCAS system in order to maintain proper airspeed and altitude. Unfortunately, despite pilots' trials to raise the nose of aircraft, the MCAS triggered more than 21 times and in the end, the aircraft collapsed in sea [16, 18, 19].

The MCAS system has been blamed for this Boeing 737 Max crash in Indonesia. The role of MCAS was to compensate for a design change to the twin engines from past 737 generations. The Max's engines are larger and mounted farther forward on the wings and this brought issues about aerodynamics of aeroplane. MCAS is a special technology which automatically lowers the nose of airplane in order to head off an aerodynamic stall. MCAS can detect critical flight situations and can intervene in the event of an imminent stall. MCAS would automatically swivel up the horizontal stabilizer, so air flow would push the tail up and push nose down. This MCAS system has been designed to prevent the airplane stalling when making steep turns under manual control. However, if a sensor gives a false reading, MCAS may activate and push the nose down when nothing is wrong with the airplane [20]. A stall can occur when the plane flies at very steep angle and this can reduce the lift generated by the wings, and has the risk to make the airplane to drop. In order to recover from a stall, a pilot would normally push down the nose of airplane. For the Boeing 737 Max, MCAS does this automatically and moves the aircraft back to a normal flight position. MCAS repeatedly takes action if it detects the plane is still tilted at too high angle [16, 19].

On a previous day prior to the Lion Air Flight JT 610 crash, the same airplane encountered problems via Denpasar to Jakarta because of a broken AOA sensor. A pilot issued the second-highest warning because of problems with MCAS system. But fortunately at that time, the flight was saved because of another pilot which was commuting to Jakarta and helped the crew to disable in time the MCAS system. The flight was continued with manual trim without auto-pilot until landing [19].

After the Lion Air Flight JT 610 Boeing 737 Max 8 crash, Boeing company issued guidance to pilots on how to manage MCAS system. As a note, prior to this disaster, information about MCAS was not included in pilot manual. However, a software fix in order to remedy the problem has been repeatedly delayed by Boeing until the next crash occurred six months later [16, 20].

*4.2. Ethiopian Airlines 302 crash in 2019, Ethiopia*

On 10 March 2019, the The Boeing 737 MAX 8, registered ET-AVJ with flight ET302 took off from Addis Ababa, Ethiopa, at 08:38 local time (05:38 GMT). The flight was supposed to be a two-hours flight and had as destination Nairobi, in Kenya. However, the Ethiopian Airlines Boeing 737 MAX 8 crashed soon in a field, just six minutes after take-off, at 08:44, almost 30 miles (about 50 kilometers) southeast of the airport, near the town of Bishoftu, south of Addis Ababa. All 149 passengers and 8 crew members on board lost their lives [16].

At the time of crash, the aircraft had only around 1,200 hours of flight time since Boeing delivered it to Ethiopia in November 2018. This airplane, underwent on 4 February 2019 a very rigorous first check maintenance and earlier on Sunday, had flown from Johannesburg, South Africa, without any incidents on board. The Boeing 737 Max which crashed in Ethiopia was part of 30 airplanes of this Boeing model which were ordered by the Ethiopian Airlines [16, 17].

Very shortly after taking-off, two sensors measuring the AOA began to record different readings. One of the sensors particularly was giving erroneous readings and this triggered the MCAS safety system which activated and forced the nose of airplane down. The pilots tried very hard to deal with the MCAS system and repeatedly disengaged it and manually tried to steady

the airplane and to control the aircraft's angle of flight. However, the MCAS prevailed in the end, and pushed down the nose of the aircraft until it crashed. The black box flight recorders, more precisely the flight data recorder and cockpit voice recorder of the Ethiopian aircraft have been under scrutiny of the investigators in Paris. It was announced that an official report will be issued within one year after this disaster [16].

## 5. Discussions

Analysis of the Lion Air Flight JT 610 and the Ethiopian Airlines Flight ET302 crashes identifies similarities among flight data. The vertical speed readings which indicates how fast a plane is going up and down, were erratic for both airplanes in Ethiopia and Indonesia and are a part of evidence that the pilots in both countries encountered big difficulties in maintaining a stable ascent of the aircraft very soon after taking-off. Furthermore, the US Federal Aviation Administration (FAA) declared that evidence which was collected from both satellite data and site brought to attention that both airplanes in Ethiopia and Indonesia behaved very similarly after taking-off until the crush moment. Moreover, in Ethiopia, a piece of wreckage from the tail of aircraft was found and showed that before the crush the horizontal stabilizers were set to point down the nose of aircraft. Both Lion Air Flight JT 610 and the Ethiopian Airlines Flight ET302 encountered difficulties with the MCAS system which automatically pushes the aircraft's nose down, or automatically trims the aircraft if it detects a stall [21].

The older Boeing 737 models do not have the MCAS system which its role is to quickly fix the aerodynamic problems which emerged after testing in 2012. the MCAS system was allowed to be triggered on impulse of a single sensor [17, 20]. In the beginning of May 2019, Dennis Muilenburg, the Boeing CEO, acknowledged that the automatic flight control system played a role in both crashes in Indonesia and Ethiopia. He declared that "The full details of what happened in the two accidents will be issued by the government authorities in the final reports, but, with the release of the preliminary report of the Ethiopian Airlines Flight 302 accident investigation, it's apparent that in both flights the Maneuvering Characteristics Augmentation System, known as MCAS, activated in response to erroneous angle of attack information" [22].

After the crash of Ethiopian Airline 737 Max airplane, the Boeing company and the FAA were heavily questioned by the US regulators and safety experts around the world, particularly, about evaluation of the anti-stall system, and about the training which was offered to pilots around the world. An important issue concerns the AOA signal reading and the MCAS's dependence on a single sensor. As the case studies of the Boeing 737 MAX 8 crashes in Indonesia and Ethiopia have shown, the malfunctions of sensors has a negative impact on functioning of system and contributes to its collapse. Moreover the probability of hazardous MCAS malfunctions (catastrophic failure) was calculated as virtually inconceivable. Boeing came up with a probability for this MCAS failure of about once every 223 trillion hours of flight. In its first year in service, the MAX fleet logged just 118,000 flight hours. Furthermore, the failure analysis did not consider the possibility the MCAS could triggered repeatedly. In addition, Boeing never flight-tested a scenario in which a broken angle-of-attack sensor would triggered MCAS. During flight testing in 2016, and in order to compensate for other issues, the scope and power of MCAS were further extended [20].

Bekker [5] and DNV-GL [7] drew also attention that the collapse of sensors and data quality to the model are critical for the digital twin. Bekker [5] emphasized that with regards to digital twin, the technological challenges remain, particularly those ones related to the sensor technology. The increased communication capabilities and increased number of sensors brought security issues in order to safely enable the digital twins [5]. Furthermore, with regards to the digital twins and sensor monitoring, the DNV-GL highlighted that a crucial aspect is given by sensor data quality which is a key requirement among industry and authorities [7].

The measurement data are provided to the digital twin through the sensors, which are critical

for their inputs to the virtual model, see the digital twin steps presented in Figure 2. A malfunction of a sensor, wrong input to model and model associated with a high uncertainty and not designed to consider most of scenarios, all of these present a high risk and ultimately, it can lead to a disaster. According to Johansen and Nejad [8], a data driven model is often used in the marine industry rather than physical-based, primarily due to lack of information of the system parameters.

Another important aspect of digital-twin relates to the real-time digital twin and near-real-time results. A slow processing of data or analysis models will bring a time-lag between measurements and the digital twin model [5]. The digital twin needs to have the ability to update dynamically in real time /near real-time as the state of the physical asset evolves and suffers changes over the time, or in the other words, the physical asset is getting older. The digital twin needs to experiment the same environmental conditions, to develop over the life-cycle like the physical asset and to get continuously updated.

Other critical aspect for the digital twin implementation concerns the role of experts. A digital twin requires various efforts and skills, and interpretation and utilization of its results needs different expertise and training. An interdisciplinary approach is highly required [5]. Moreover, as per DNV-GL [6], the digital twin brings together experts from various fields and requires long-term collaborations and integration of expertise. However, a world of experts requires learning, diversity, acceptance, collaboration, and interdisciplinary approach.

DNV-GL [6] proposed an extension of the Digital Twin concept, the so-called Probabilistic Twin. While the digital twin is a digital copy of a physical asset, the Probabilistic twin is a forecasting tool in order to support the risk management of asset's operation. The Probabilistic twin couples the digital twin to risk models which are continuously updated based on existing knowledge and actual conditions. Nevertheless, before moving beyond digital twin, the implementation of the digital twin is associated with uncertainties.

The Boeing accidents highlight that the consequences of a faulty digital twin can be very severe and can contribute to major accidents and disasters. These Boeing accidents can be seen through different views or perspectives related to the digital twin: through the sensors malfunctions and software malfunctions, through the faulty verification of the new MCAS system through digital twin and simulators, faulty model, through wrong data-analysis, failure to predict risky scenarios and wrong decision making. These views indicates the importance of sensor reliability, importance of right input measurements, risk of decision making based on wrong input measurements, and significance of better modelling, simulations and verification. The Boeing accidents can be seen as examples of risks associated with digital twin main steps as presented by the Figure 2.

The MCAS system had been tested via digital twin and through simulations, but later on, after disasters, Boeing acknowledged the faults linked to the MCAS simulator and flaws in the 737 Max flight simulators [23, 20]. The Boeing officially announced the updates of MCAS system in May 2019:"MCAS is designed to activate in manual flight, with the airplane's flaps up, at an elevated Angle of Attack (AOA). Boeing has developed an MCAS software update to provide additional layers of protection if the AOA sensors provide erroneous data. The software was put through hundreds of hours of analysis, laboratory testing, verification in a simulator and two test flights, including an in-flight certification test with Federal Aviation Administration (FAA) representatives on board as observers" [21]. The faulty software linked to MCAS system has been further confirmed through additional layers of protection not limited to: flight control system will compare inputs from both AOA sensors, and MCAS can never command more stabilizer input than it can be counteracted by the flight crew. The pilots will always have the ability to override MCAS system and to manually control the airplane [21].

Nevertheless, during simulator testing of the software changes, the Federal Aviation Administration had identified in June 2019, a new potential risk which is required to be settled
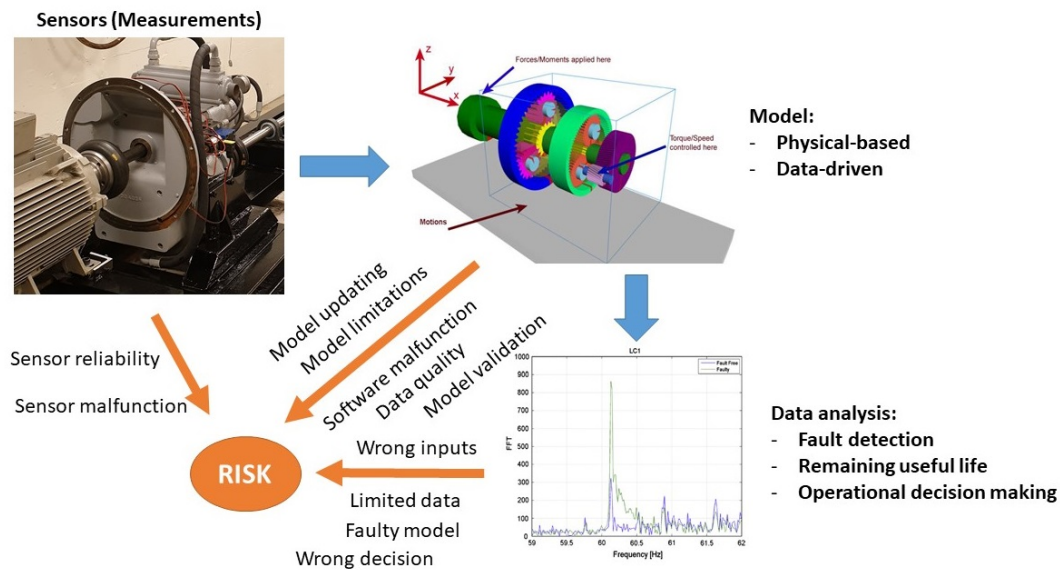
**Figure 2.** Examples of risk associated with digital twin main steps.

by Boeing. This matter relates to the runaway stabilizer trim, an uncommanded movement of the horizontal stabilizer, the little wing near the tail which moves the plane up or down. If the pilots are unable to correct it and a microprocessor will fail, then, there is the risk of plane crash [24].

The aviation industry is very advanced in implementation of digital twins [2, 3, 4] and the digital twin has been used much earlier and for longer time in this industry in comparison with marine industry. However, it was identified that the aviation industry still confronts major challenges associated with implementation and development of digital twin. Nowadays, the technological trend of digital twin is growing fast in marine industry, however the implementation of the digital twin in marine industry is not so well developed like in the aviation industry.

The aviation and marine industry are different industries, however with regards to the risk of digital twin implementation, some common traits can be identified.

First, the essential steps of the digital twin as presented by Figure 1 are common steps for both digital twin in aviation industry and digital twin in marine industry. Second, both industries pose risk to people, properties, business and environment. Third, the structures in both aviation and marine industry are subject to dynamic environmental forces; for example, in aviation industry, there is wind, temperature, air density, and in marine industry, there is wind, waves, current load, tidal currents. Moreover, in both industries, there are dynamic electro-mechanical systems which are used to transfer and convert energy and control of structures such as airplanes, ships and other offshore or marine structures. Thus the lessons and learning from aviation industry with regards to risk posed by digital twin can have high value among other industries, particularly, in the marine industry. Moreover, a reactive learning from major accidents and disasters needs to be continuously supported by a proactive learning and a dynamic risk culture [25].

## 6. Concluding remarks
The digital twin presents many advantages, however the implementation of the digital twin is associated with high risk and high uncertainties which must be addressed, even within the

industries like aviation industry where the digital twin is well established and at a more advanced level than in the marine industry.

An essential lesson from the aviation industry towards marine industry is that the implementation of the digital twin comes with its own risk, and requires a risk assessment.

The aim of employing digital twin is to reduce the risk in operations, and therefore, the digital twin itself should not pose or bring new risk. However, the recent failures in the aviation industry show the vulnerability of sensors, and cases where the digital twin was not able to identify the system faults - software in this case - during the design and this contributed to two disasters. The digital twin used for system verification of the Boeing 737 Max product encountered failures. The digital twin was ineffective as it failed to simulate and predict those operational scenario cases which could lead to deadly accidents.

Moreover, through the case studies of disasters in the aviation industry it was found that the digital twin may not be able to represent all the possible scenarios which a system may experience during its life time.

As a paradox, the purpose of implementation of the digital twin is to reduce the risk, but the digital twin itself brings its own risk as illustrated by case studies and disasters in the aviation industry. Various challenges are associated with implementation of the digital twin and these include and are not limited to sensor reliability, sensor data quality and their input to the virtual model, uncertainty associated with model, the real-time digital twin and near-real-time results, dynamic updates to the model, the role of experts, integration of expertise, multidisciplinary approach in engineering, and collaboration and learning among industries.

Towards learning from the aviation industry recommends that a risk associated with the digital twin itself shall be assessed before the implementation of the digital twin. The digital twin comes with high uncertainties and cannot be only seen as the technological solution which shall be implemented in order to solve all the problems within the industry. A high awareness indicates that the digital twin shall not be seen only in terms of potential benefits, but comes with its own challenges and risk which need to be addressed in time.

The marine industry, particularly the autonomous ships, needs to learn from and integrate the lessons from the aviation industry with reference to the digital twin. The aviation industry has employed the digital twin for longer time than the marine industry, but still the implementation and usage of digital twin is not risk free and a complete reliance on digital twin is not feasible.

In a digital era with many complicated and highly advanced technological systems, the digital twin solution presents its own related uncertainties which need to be continuously assessed and addressed.

## References

[1] B. Marr. What is digital twin technology – and why is so important? `https://www.forbes.com/sites/bernardmarr/2017/03/06/what-is-digital-twin-technology-and-why-is-it-so-important/#43da48e42e2a`, 2017. [Online; accessed 15-Feb-2019].

[2] B. Woodrow. Boeing ceo talks digital twin era of aviation. `https://www.aviationtoday.com/2018/09/14/boeing-ceo-talks-digital-twin-era-aviation/`, 2018. [Online; accessed 15-March-2019].

[3] D. Canaday. Will digital twinning play a more important role in aircraft health monitoring? `https://www.mro-network.com/maintenance-repair-overhaul/will-digital-twinning-play-more-important-role-aircraft-health`, 2018. [Online; accessed 15-March-2019].

[4] J. Domone. Digital twin for life predictions in civil aerospace. `https://www.atkinsglobal.com/~/media/Files/A/Atkins-Corporate/Digital%20Twin%20White%20Paper%20v6.pdf`, 2018. [Online; accessed 15-March-2019].

[5] A Bekker. Exploring the blue skies potential of digital twin technology for a polar supply and research vessel. In *Marine Design XIII, Volume 1*, pages 135–145. CRC Press, 2018.

[6] DNV-GL Maritime. *Digital twin report for DMA, Digital Twins for Blue Denmark, Danish Maritime Authority, Report 2018-0006*. DNV-GL, 2018.

[7] DNV-GL. Digital twins and sensor monitoring. `https://www.dnvgl.com/expert-story/maritime-impact/Digital-twins-and-sensor-monitoring.html`, 2019. [Online; accessed 23-Jan-2019].

[8] S. S. Johansen and A. R. Nejad. On digital twin condition monitoring approach for drivetrains in marine applications. In *ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers, 2019.

[9] S. S. Johansen. On developing a digital twin for fault detection in drivetrains of offshore wind turbines. Master's thesis, Marine Technology Department, NTNU, 2018.

[10] General Electric. Renewable energies 2019. digital wind farm. `https://www.ge.com/renewableenergy/digital-solutions/digital-wind-farm`, 2019. [Online; accessed 15-April-2019].

[11] M. Grieves. *Product Lifecycle Management, Driving the next generation of lean thinking.* McGraw-Hill, 2006.

[12] S. O. Erikstad. Design patterns for digital twin solutions in marine systems design and operations. In *The 7th International Conference on Computer Applications and Information Technology in the Maritime Industries, COMPIT 2018, Pavone, Italy, 14-16 May 2018*, 2018.

[13] E.J. Tuegel, A. R. Ingraffea, G.T. Eason, and S.M. Spottswood. Reeingineering aircraft structural life prediction using a digital twin. *International Journal of Aerospace Engineering*, page 154798, 2011.

[14] J. Torsvik, A. R. Nejad, and E. Pedersen. Main bearings in large offshore wind turbines: development trends, design and analysis requirements. *Journal of Physics: Conference Series*, 1037(4):042020, 2018.

[15] Y. Tian. Development and application of digital twin in marine propulsion system. Master's thesis, Marine Technology Department, NTNU, 2019.

[16] BBC. Boeing 737 max: What went wrong? `https://www.bbc.com/news/world-africa-47553174`, 2019. [Online; accessed 8-April-2019].

[17] Deutsche Welle. Boeing 737 max: a plane of compromise. `https://www.dw.com/en/boeing-737-max-a-plane-of-compromise/a-47852944`, 2019. [Online; accessed 15-May-2019].

[18] KNKT. Komite Nasional Keselamatan Transportasi Republic of Indonesia: Preliminary KNKT.18.10.35.04, Aircraft Accident Investigation Report, PT. Lion Mentari Airlines, Boeing 737-8 (MAX); PK-LQP, Tanjung Karawang, West Java, Republic of Indonesia, 29 October 2018. `https://reports.aviation-safety.net/2018/20181029-0_B38M_PK-LQP_PRELIMINARY.pdf`, 2018. [Online; accessed 15-Feb-2019].

[19] Aviation Tops. More shocking facts about the Boeing 737 Max crashes. `https://www.aviationcv.com/aviation-blog/2019/shocking-facts-boeing-737max-crash`, 2019. [Online; accessed 1-April-2019].

[20] D. Gates and M. Baker. The inside story of MCAS: how Boeing's 737 Max system gained power and lost safeguards, . `https://www.seattletimes.com/seattle-news/times-watchdog/the-inside-story-of-mcas-how-boeings-737-max-system-gained-power-and-lost-safeguards/`, 2019. [Online; accessed 05-July-2019].

[21] Boeing. 737 Max updates. `https://www.boeing.com/commercial/737max/737-max-software-updates.page`, 2019. [Online; accessed 20-May-2019].

[22] Telegraph. Boeing crash payouts would be partly based on how long passengers knew they were doomed. `https://news.yahoo.com/boeing-crash-payouts-partly-based-160054887.html`, 2019. [Online; accessed 12-May-2019].

[23] Financial Times. Boeing admits flaw in 737 Max flight simulator. `https://www.ft.com/content/494354da-799e-11e9-81d2-f785092ab560`, 2019. [Online; accessed 20-May-2019].

[24] C. Woodyard. FAA finds new potential risk in Boeing 737 Max, a setback that could delay plane's return to the sky, USA Today, . `https://eu.usatoday.com/story/news/nation/2019/06/26/boeing-737-max-new-potential-risk-could-delay-jets-return-skies/1577597001/`, 2019. [Online; accessed 29-June-2019].

[25] M. Ibrion, N. Paltrinieri, and A. R. Nejad. On disaster risk reduction in Norwegian oil and gas industry through life-cycle perspective. In *ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers, 2019.