ORIGINAL ARTICLE

Trade Study to Select Best Alternative for Cable and Pulley Simulation for Cranes on Offshore Vessels

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Cranes on offshore vessels are subjected to crane dynamics, structural couplings to the vessel, and environmental influence by waves and currents. The recent trend has been to use larger cranes on smaller vessels, which makes the lifting operation even more complex. The use of Digital Twins (DTs) are of emerging interest as they enable safer operations, real time simulation and maintenance prediction. On offshore vessels, a DT can monitor the lifting operation to create a safer work environment. The SPADE model has been used as a framework towards the creation of a DT of cranes on offshore vessels. As part of this, several cases involving simulation of cranes revealed the lack of an adequate simulation of cable and pulleys suitable for DTs. This is important for accurate results and for implementation in control systems. A trade study was performed to detect a numerical method adequate for cable and pulley simulation. The trade study identified the Absolute Nodal Coordinate Formulation (ANCF) in the framework of Arbitrary Lagrangian–Eulerian (ALE) as a promising numerical formulation.

KEYWORDS
Digital Twin, MBS, FEM, Crane, Cable, Pulley, Simulation

1 | INTRODUCTION

Offshore vessels with cranes are used for operations such as installation of subsea templates, offshore wind turbine installation, and loading and unloading of equipment. Wind, waves and currents complicates these operations. The recent trend has been to use smaller vessels, with larger cranes, due to cost savings. This makes the lifting operation even more subjected to instability due to the environmental excitations. A Digital Twin (DT) of an offshore crane allows for safer lifting operations. It enables prediction of the load movement and compensation with the control system, improved heave compensation, and monitoring of maintenance and fatigue schemes. Furthermore, a DT support identification of failure states and forecasting the condition, which the project manager can use for the risk analysis. The prediction are sensitive to the accuracy of the model the DT is based on.

A step towards creating a DT of a crane on offshore vessels are to improve the simulations. This paper is set to investigate the requirements for improved simulations. The structure of this paper is as follows: First, the paper presents a context diagram of crane dynamics for a better understanding of physics and dynamics, with the theoretical background for simulation. Then stakeholders are identified to investigate different interests in the project. The main body of the paper then follows with pointing out shortcomings for crane simulation according to cases and previous research. Here it is observed that cable and pulley simulation is lacking accuracy, and a better simulation of cable and pulleys will assist a DT. Based on design requirements a trade study is performed to investigate alternatives for different numerical methods for dynamic simulations of cable and pulleys to create a DT. For a DT the real time simulation aspect is of importance. The paper is wrapping up with a decision making on present results and further work. The paper follows the SPADE methodology as proposed in Haskins (2008).

2 | BACKGROUND

DT is a wide term, so Schluse and Rossmann (2016) lists several companies where the term DT is used differently for industrial practices: Manufacturing flexibility, product design, maintenance, increased lifetime, testing, structural monitoring, efficiency, quality and automation. A DT can be used, not only for engineering and manufacturing, but also operation and service, which according to Boschert and Rosen (2016) makes it more than a Multibody Systems (MBS). This implies that the DT could become a part of the real system, with actionable interactions. In Grieves and Vickers (2017) DTs are divided up into several subgroups. DT Instance, which "describes a specific corresponding physical product that an individual DT remains linked to throughout the life of that physical product", is the most relevant for a crane. Schluse et al. (2017) describes a similar type of DT, which he calls Experimental DT. He claims that “Experimental Digital Twins” seem to have the potential to close the gap between Systems Engineering (SE) and simulation by introducing a new structuring element to configure simulations with virtual test-beds. DTs allows for testing prior to manufacturing, which can lead to significant cost savings. For Product Lifecycle Management (PLM) Tao et al. (2018) has proposed a new method for DT-driven product design, manufacturing and service. The product design phase is divided up into conceptual design, detailed design and virtual verification.

The context diagram as presented in figure 1 is a helpful tool to take a step back and get the bigger picture for creating a DT of an offshore crane. For an offshore lifting operation, the environment with wind and wave induced motions affects the operation. The lifting operation could take place in harsh environments or at the harbour. For lifting operations involving other vessels, the vessels will be in different swing phases. Maintenance is a critical part for the crane to be operational. To allow for a DT it is required to instrument the physical crane with sensors. The draw work of the crane is an essential part of the lifting mechanism. The crane operator is responsible for safe lifting operations, and therefore could be willing to work in harsher environments with better monitoring. The control system could use an active or a passive heave compensation system to help stabilize the load in waves, and in addition compensating for the relative motion between vessels to keep the load at relative rest. The hydraulics of the crane causing time delays will be included in the DT. The goal is to be able to simulate the whole crane system. This includes how the boom deflects, pulleys, bearings, inertia effects, friction and damping. The inherent dynamics and friction effects in a crane may cause out of phase tension oscillations in the cables, which again leads to control system instabilities. The frequency on the bearings could be influential when it comes to decoupling the crane for simulation, without significant loss of accuracy. The elasticity in the cable, lateral and longitudinal frequencies are affected by the loading condition. Cables has an ability to withstand large axial loads in comparison to bending, compression, and torsional loads. The cable pulley interaction is important, where contact and friction has to be defined. The context diagram highlight that crane dynamics are influenced by cable and pulleys.

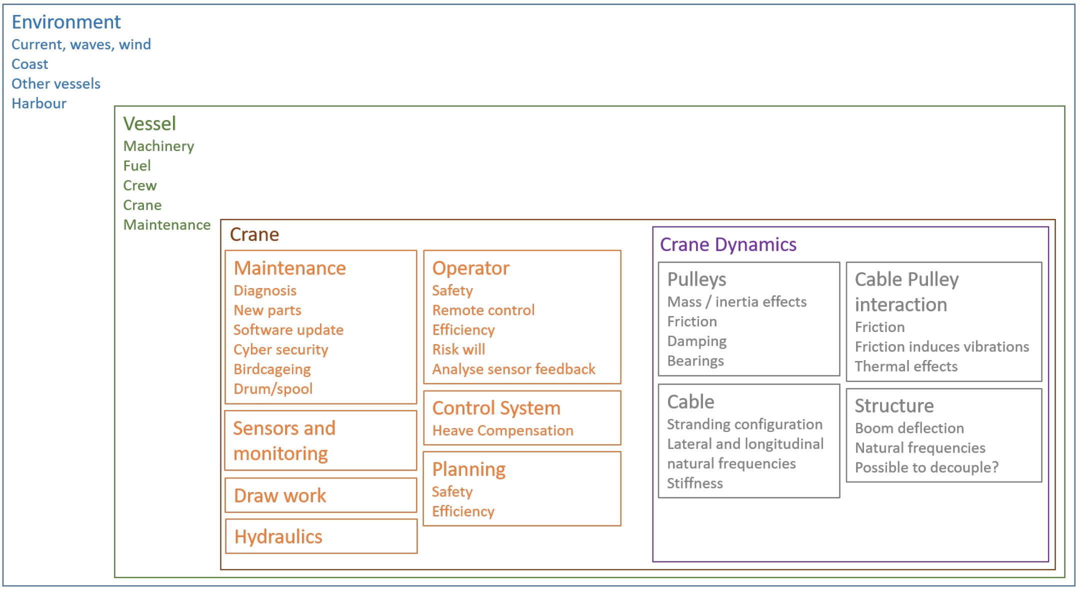

FIGURE 1 Context diagram for the crane dynamics of cable and pulleys.

FEA (Finite Element Analysis) as applied in engineering is a computational tool for performing engineering analysis typically for design and optimization. It can be used both for static and dynamic simulations, where dynamic simulations is stepping through a given time interval. An important difference between an engineering simulation and a DT is that a simulation cannot foresee future scenarios and changing circumstances. DT on the other hand takes in real time sensor data and updates the simulation, as it is stepping trough time. This gives the engineer a much better insight in what is actually happening. The real time aspect is a key, and requires fast calculations. Therefore, the purpose of FEA is now to be operational as an estimator, instead of design and optimization. FEA are numerical methods, or formulations, where the Finite Element Method (FEM) is one of them. FEM is commonly used for failure assessment, fracture and crash simulation. FEM is more relevant for crane simulation than other numerical methods, such as rigid body simulation, since it accounts for the flex in the crane boom during heavy lifting, Hong et al. (2016). There are numerous software on the market doing simulations based on FEM. FEM works by dividing the Computer Aided Design (CAD) model into many small pieces called elements, see figure 2. The elements have material and geometrical properties. Then forces and boundary conditions are included in the model. Mathematical equations describes the behavior of the elements, and how they interact with each other during the simulation. There are numerous elements with different characteristics, specialized for certain simulations.

A MBS consist of several sub-models, which makes up the system being simulated , see figure 2. The different parts have a CAD model, which could be used as a rigid body, or meshed with finite elements for elastic behavior. Mechanism modelling use joints to connect the parts for interaction. Control system modelling is used for actuators, like the hydraulic cylinders and the virtual sensors. The 1D flow chart presents an example of a control system, where real or virtual sensors can be the position input. The applied force will be set according to deviation in measurement and reference value. Cable and pulley modelling is usually simplified to an axial spring.

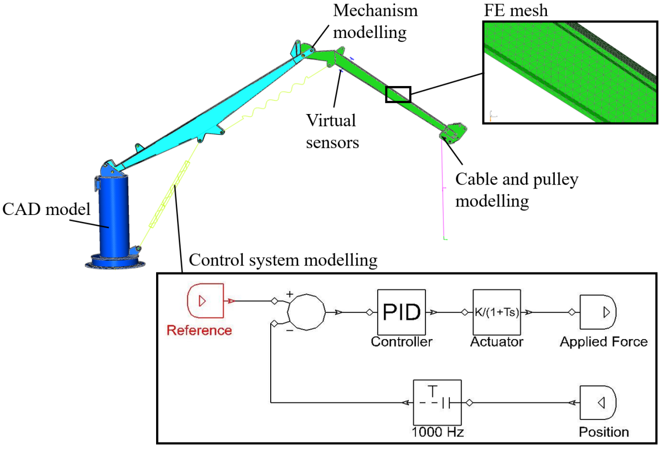

FIGURE 2 The crane system with different sub-modelling requirements indicated.

A simple example of a DT is found in figure 3. In this illustration, the Physical Sensor Data (PSD) from the physical crane is stored in a state vector, which contains turn angle, stroke length of actuators and applied load at the crane tip, $PSD(t) = [\Delta L1, \Delta L2, \Delta\Theta, mg]$. The state vector is time dependent. The dotted arrow indicates how the state vector is transferred to the server cloud. The digital crane model retrieves the $PSD(t)$ from the cloud, for calculations. Based on the input from the physical crane, the inverse method can be used to extrapolate forces and strains to virtual sensors in the digital model. While the physical actuator are measuring stroke length, the reaction forces can be found in the digital actuators. Also the strain history can be found for any part of the crane, by virtual sensors. This is relevant for detecting fatigue failure. Direction and size of forces are relevant for detecting stability issues and critical loads. The digital model can have an infinite number of states, free of charge. The outputs from the digital crane, Digital Sensor Data (DSD), are stored in the state vector $DSD(t) = [F1, F2, M, \epsilon 1, \epsilon 2, \epsilon 3, \epsilon 4]$, and sent to the cloud. The data in the cloud could further be used for visualization and presentation of results. The weather and wave forecast are additional data relevant to store in the the server cloud, for risk analysis of the job.

In the video posted by Raftery (2017), a DT is demonstrated by a simple beam with a sensor at the top end, which allows for the whole stress distribution in the beam to be calculated. Different colors indicates the stress level in the beam. The stress is a consequence of the force applied by the hand. The inverse method refer to the numerical equations

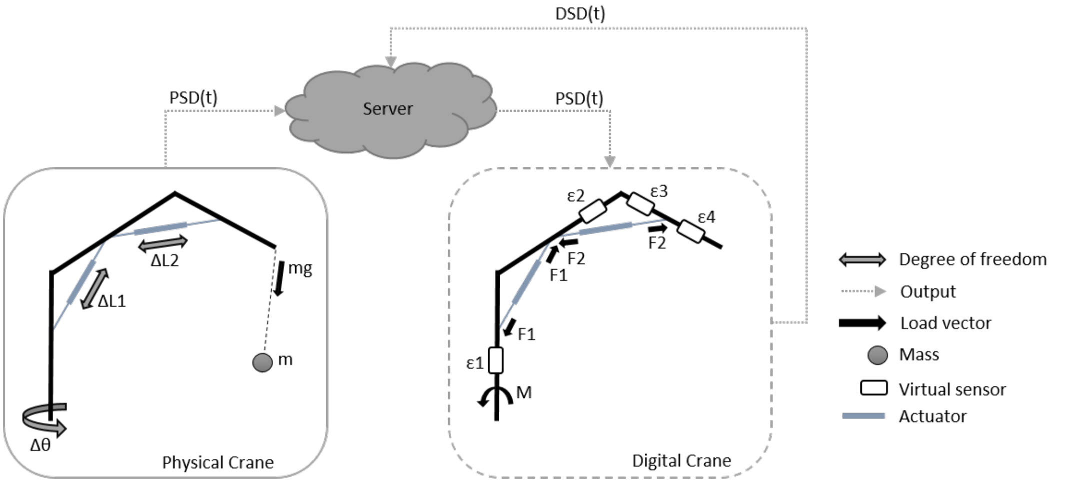

FIGURE 3 Sensors on the physical crane sends real time measured data to the DT. By the inverse method, the DT distributes the inputs to virtual sensors.

in a simulation, where the input data is a measured value, and the DT behaves accordingly. There are several ways to do the inverse calculations, and there is a need for inverse methods that accurately calculate distributed displacements, frequencies or loads, in order to predict the structural integrity. Solvers have to be accurate and time efficient, as the time of the simulation has to be less than the physical time for a real time DT. Further discussion of inverse methods are outside the scope of this paper. The fact that physical sensors are expensive while virtual sensors are free of charge, as well as the real time aspect, makes the DT gain momentum. Challenges related to what sensors to use, where to install them, and how to process and filter the data from the sensors will not be addressed in this paper.

3 | RESEARCH METHOD

When exploring new complex systems, it is useful to structure the relevant information. This increase the possibility for making good decisions, expose gaps, problem solving, as well as moving forward faster. Systems Engineering (SE) provide tools to handle this. To create a reliable and robust DT of an offshore crane is new technology. This makes SE tools highly relevant and useful for such a development project.

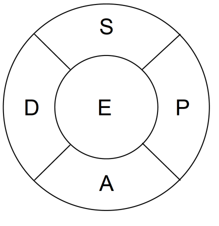

FIGURE 4 "SPADE methodology/framework graphical representation" Haskins (2008).

The SPADE methodology was introduced by Haskins (2008), see figure 4, and was used as the research method in this paper. SPADE is an acronym constructed from the words: Stakeholders, Problem, Alternatives, Decision-Making, and Evaluation. Evaluation is a continuous process, and is therefore placed in the center of the figure. During the evaluation process, one update the old findings by new and relevant information. This makes the SPADE methodology useful for dealing with problems where the destination is unknown. It also helps to give relevant answers according to what the stakeholders actually desire for a DT of an offshore crane, as the stakeholders are pointed out early on in the design process. During the evaluation process a consultation with the stakeholders can be done, to discuss preliminary proposals. New stakeholders can also be included during the evaluation process. The Problem stage exposes lacks in technology for the creation of a DT of an offshore crane. Based on the Problem stage, different solutions are compared in the Alternatives stage. To evaluate and compare alternatives for a numerical formulation for cable and pulley simulation, the trade off analysis tool based on Blanchard and Fabrycky (2006) was used, see figure 5. For the "Evaluation of the design requirement" step in the trade of analysis, a table based on the subjective value method was used according to Kossiakoff et al. (2011). The subjective value method weight the characteristics of each formulation against each other to find the one that best suite the system as a whole, according to design requirements. The score given was based on papers describing the features. Extensive testing of all the alternatives for cable and pulley simulation would be inadequate due to being very time consuming to implement, making the trade study more suitable. To make a qualified decision based on available information allows for the project to move forward with a steady pace. Decision-Making is the final stage in the SPADE methodology, where the best alternative for a DT is chosen.

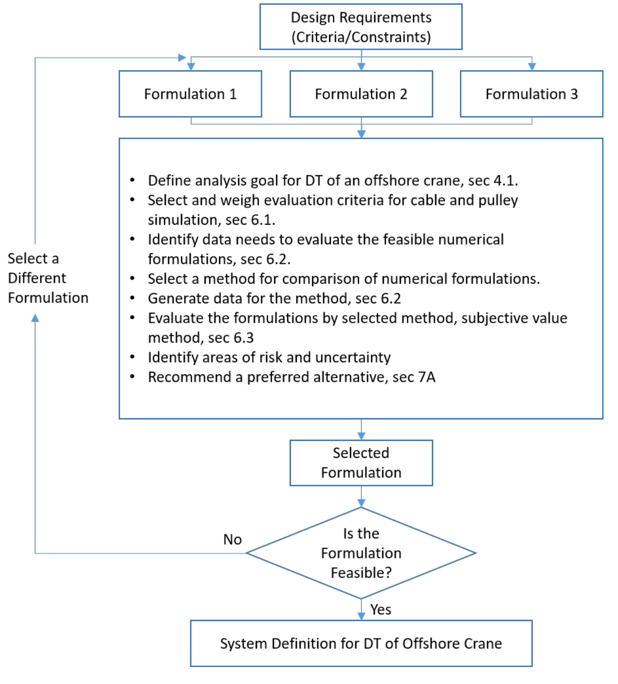

FIGURE 5 Trade-off Analysis Process, based on Blanchard and Fabrycky (2006).

4 | IDENTIFICATION OF SYSTEM STAKEHOLDERS AND NEEDS

Grieves and Vickers (2017) points to siloing, knowledge of the physical world, and the number of possible states that a system can take as the main challenges for a DT. Siloing is referring to lack of communication between the different groups working on the same project. The issue of siloing is addressed by finding who the stakeholders are, and involving them in the project. A stakeholder is defined by Freeman and McVea (2001) as "any group or individual who is affected by or can affect the achievement of an organization's objectives". Stakeholders have interest in the project in some way or another, and with that have expectations to the outcome. To deliver a product that answers to the expectation, it is important to identify who the stakeholders of the project are. If the stakeholders have conflicting interest, this will be discovered.

This paper started out by the desire to create a DT of a crane on offshore vessels for safer lifting operations. The stakeholders was identified, for involving expertise on all area as well as solving the right problems and creating the needed product. Based on insight from the stakeholders both application for DTs, and cases where gaps for creating a DT, was discovered.

In figure 6 the stakeholders for a DT of a crane are listed:

- SFI Mechatronics, which represents The Research Council of Norway function as a bridge builder for knowledge flow between academia and the industry. Their goal is to strengthen competitiveness and innovation capacity in Norway. They want to develop high-quality research groups. This research is part of a project with a vision to create «advanced offshore mechatronic systems for autonomous operation and condition monitoring of topside drilling systems under the control of land-based operation centers, to ensure safe and efficient operation in deeper water and in harsh environments».
- Crane producers are interested in making safe and reliable products. Improved simulations of cranes as well as real time feedback would help to better understand how a crane are subjected to forces during operation. This would be valuable insight for technical upgrades. The upgrades are based on what the operator, manufacturers and owners requests for the products.
- Operators of cranes wants faster and safer lifting operations. More automation and control systems will provide safer lifting operation, where real time feedback is important. Fatigue analysis of both the crane structure and cables are valuable for improved lifetime assessment. A DT could here be a valuable tool for logging and failure prediction.
- Vessel manufactures are interested in installing the most suitable crane for the vessels. They are also interested in flexible solutions, which would be a competitive advantage.
- Vessel owners' wants to best handle the requirements for the job. This includes using the right equipment for the job, where the requirements for a safe job are fulfilled, with the lowest cost. It is costly to have a vessel wait for better weather conditions. Improved simulation allows for better planning for the operation prior to the execution of the job. If the waves are rougher than what the operation was planned for, a DT can analyze if the operation is still safe to execute based on real time data. Vessel owners' are also interested in better lifetime assessment for planning the maintenance jobs. A DT could minimize downtime, which equals less cost. Control systems allowing for faster and safer lifting operations are of great interest.
- Software specializing in simulation and analysis of problems concerning failure assessment, fracture and fatigue etc. are interested in improving and expanding their capability of accurate and fast calculations, for solving more intricate problems.
- Software specializing in DT solutions, where visualization and presentation of outputs are relevant, for making a

user friendly product.

- Producers of sensors and monitoring equipment used for input to a DT are interested in development of other technologies improving DTs. This will expand the use of sensors and the market for the producers.
- Industries working with other products that could benefit from new technology developed for offshore cranes. Elevators, draw works, power-lines and robotics are examples of applications with similar challenges as cable and pulley simulation.

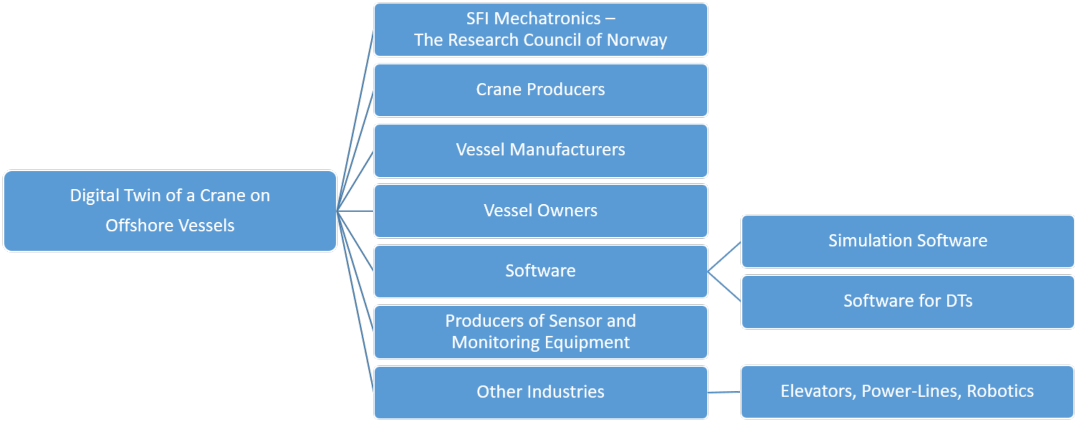

FIGURE 6 Stakeholders for a DT of a crane on offshore vessels.

4.1 | Measures of Effectiveness (MOE)

When the problem has been formulated, then criteria are put in correct term as Measures of Effectiveness (MOEs). MOEs represent the viewpoint of stakeholders and assists in making the right choices based on the stakeholders needs, Sproles (2000). This sets the success criteria for when the end goal is reached. MOEs for this project follows:

- A cable and pulley simulation improves the overall real time simulation of a crane on an offshore vessel.
- The DT of a crane results in better control systems, maintenance prediction, and faster and safer lifting operations, even in rough seas; i.e., the number of industrial injury concerning work with cranes on offshore vessels are reduced when using the DT, i.e., the operational time for cranes when using the DT is increased.

5 | PROBLEM FORMULATION

The research topics concerning simulation of offshore cranes has been relevant for a long time, where for example Strengehagen and Gran (1980) investigated the dynamic response and fatigue life of offshore cranes back in the 80's. They stated, "Limitations in the method for this application are mainly that the method is linear and that all elements are taking compression as well as tension. Both limitations are mostly concerned with the ropes." Compression forces in ropes and cables will only cause them to fold, not take up any significant force. Langen et al. (2000) published work concerning the dynamic behavior of an offshore crane. The goal was design verification against overload and fatigue. The cables in the simulation was represented as axial springs. Ku and Roh (2015) and Hong et al. (2016) are more recent studies concerning offshore cranes. The first are investigating the safety of installation of offshore wind turbines by floating cranes. This is done by simulation where wind, hydrostatic and dynamic forces are acting on the crane. The latter predicts dynamic loads on a crane on an offshore support vessel. It argues for the importance to use a flexible body model, and not a rigid body, as the boom flexes. Research addressing coupling motions between crane and vessel, how external forces acts on the crane structure, how the boom flexes and hot spots for stress are well documented. The matter of simulating MBS assembled with cable and pulleys, such as cranes, has for a long time been simplified, hence the need for more advanced and accurate cable and pulley simulation has evolved. Moseid (2017) started this work by introducing several challenges related to two-dimensional finite element based mathematical modelling of cable and pulley systems, such as inherent dynamics and friction effects in his master's thesis.

The fact that cable and pulley simulation is a short coming is also evident in the following cases from Fedem Technology and NTNU sources, presented in the next section. There are different types of cranes being investigated, and the objectives of the simulations varies. What they have in common is that they are all lacking, and would benefit of, a good cable and pulley simulation. The cases exposed the need for an improved cable and pulley simulation, which would improve simulations in general, and also for DTs of cranes. The cases will function as benchmarks for further research.

5.1 | Laboratory Crane 1 - Knuckle Boom Crane

A knuckle boom crane for testing is built in a laboratory at NTNU, see figure 7. The crane is accessible for running experiments and benchmarking. It is instrumented with strain gauges for data collection when running experiments, as well as a detailed FEM model. The FEM model does not include an advanced cable and pulley simulation, where stiffness or varying cable length is included. The goal with the crane is to detect error during lifting operation, structural integrity calculations, fatigue life prediction and stability monitoring. The insight could be used for condition based maintenance.

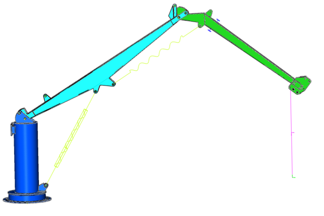

FIGURE 7 Laboratory Crane 1 is a knuckle boom crane built in one of the laboratories at NTNU, with a detailed FEM model of the crane.

5.2 | Laboratory Crane 2 - Knuckle Boom Crane

A knuckle boom crane for testing in a wave pool, is located in a laboratory at NTNU, see figure 8. This allows for testing to study how the vessel movements affects the lifting operation, and what response this will have in the crane and the payload. The hydrodynamics must be included in the simulation. Limits for when the system becomes unstable are relevant to find, and what the main factors that influence the stability are. Critical payloads, wave and wind conditions are relevant to examine. Furthermore, active damping can be studied.

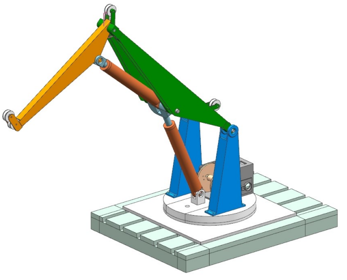

FIGURE 8 Laboratory Crane 2 is a knuckle boom crane for testing in a wave pool.

5.3 | Johan Sverdrup - Tower Crane

Structural vibrations in the tower cranes on the oil rig Johan Sverdrup has been investigated, see figure 9. The FEM model of the oil rig is very detailed. FEM accounts for internal deformations in the crane, which is a reason to use it for analysis of structural flexibility. The crane is a complicated system with delay in the system with boom flex, hydraulics and tension in the cable. Since the frequency in the cable change with varying length, mass and stiffness in the cable, an improved cable and pulley simulation could make the over all results even more accurate for this case.

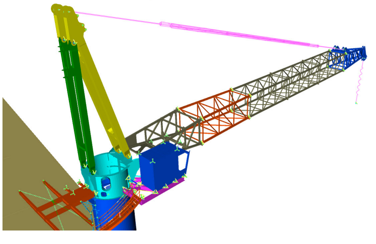

FIGURE 9 Tower crane installed on the oil rig Johan Sverdrup.

6 | ALTERNATIVES FROM TRADE STUDY

To identify the best alternative feasible as a numerical formulation for cable and pulley simulation, a trade-off analysis based on Blanchard and Fabrycky (2006) has been performed, see figure 5. The main interest for this project is to improve the overall behavior of a crane. To include effects such as interactions between the strides in the cable demand additional computing power. This could jeopardize the real time aspect for a DT. For offshore cranes, the demands for dynamics are set higher than for onshore cranes with lower movements. A pulley rotates from friction when the cable moves over it. If the friction is too low, the cable will slide over the pulley instead of rotating it. When the draw work stop pulling the cable, the rotational inertia in the sheaves could cause the cable to move. To simulate these effects, the numerical formulation must include contact and friction. Accidents during lifting operations could have severe consequences, and in worst-case fatal accidents. A risk analysis is therefore critical prior to lifting operations. The equipment used must be trusted. If an operational FEA is going to be used as an estimator for controlling the crane, it must be proven reliable and stable prior to being put to use. This imply that the formulation must handle different simulation scenarios. If the control system fails, the crane could suddenly drop the load, jerk the load, or stop running. Tested formulations known to be stable and robust should be used to prevent this. Design requirements for a formulation of a cable and pulley simulation follows in the next section.

6.1 | Design Requirements

1. The simulation method should be compatible with FEM, as FEM is commonly used for simulations of crane systems.
2. Dynamics in the cable, where mass, damping and inertia effects are included. This is important to predict reaction forces, the shape (mode shapes), and position of a cable in motion.
3. Contact and friction between cable and pulley, and between different cable segments.
4. Acceptable computational speed, due to the real time aspect of a DT.
5. Time varying cable length, with mass updated accordingly. This is important for correct axial stiffness for applications where the cable is lowered or elevated.
6. Reliable formulation with documentation proven to be extensively tested.

6.2 | Alternatives for Cable and Pulley Simulation

Based on the MOEs, stakeholders and design requirements, alternatives for cable and pulley simulation are identified:

6.2.1 | Spring

In FEA a cable has commonly been represented as an axial spring, Langen et al. (2000) and Arena et al. (2015). This is derived from Hooke's law, $F = -k * x$, where , F is the force, k is the spring characteristic and , x is the axial displacement. For more advanced behavior the spring characteristic can be tabulated dependent on the cable length. This formulation neglects mass and inertia forces. Only axial stiffness is included in the cable dynamics. The normal forces on the draw work and pulleys are therefore not considered. The approach results in fast calculations, and can provide sufficient results for certain simulations. The formulation is reliable, as it is simple and has been extensively tested.

6.2.2 | Isogeometric Analysis (IGA)

Raknes et al. (2013) use Isogeometric Analysis (IGA) to describe large deformations in a 3D cable. Ribs of an umbrella and bow and arrow are numerical examples used. Thai et al. (2017) published a paper concerning static application of cables with IGA. The textbook Cottrell et al. (2009) describes how IGA relates to FEM. Instead of generating a mesh, IGA do calculations directly on the CAD geometry. It is possible to have IGA and FEM to interact, but it would be challenging in more advanced models where nodes in the mesh and CAD geometry not necessarily coexist and merge. IGA still suffers from some numerical challenges, and the major drawback is that it struggles to handle contact analysis, Cardoso and Adetoro (2017). The use of IGA would involve a risk, as the formulation is less mature than FEM, and possible complications when combining with FEA.

6.2.3 | The Bar Finite Element for Cable

The bar finite element as described in Priour (2013) is based on a principle to split the bar element into perfectly straight, homogeneous elements. The elements have elastic properties without rotational Degrees of Freedom (DOFs). Trough a coupling between consecutive bar elements, bending stiffness is included. This leads to forces on the extremities of these two elements when a curvature occurs on the modelled cable. A large amount of elements is required for an exact representation of the cable. The formulation includes drag forces from water, and has been tested for simulation of fish cages and fishing gear.

6.2.4 | A Parametric Super Element

Ju and Choo (2005) presents a super element formulation for a cable passing through several pulleys. The method has the ability to represent complex geometric paths for a long cable. A tower crane has been analyzed by this formulation. Static simulations is the primary target for this formulation; therefore, it neglects the dynamic behavior of the pulley.

6.2.5 | The Floating Frame of Reference Formulation (FFRF)

According to Shabana (1997b), Floating Frame of Reference Formulation (FFRF) was the most widely used formulation for simulation of flexible MBS, in 1997. In FFRF there are two sets of coordinates used to describe the configuration of the deformable bodies; the rigid is described in the global coordinate system, while the local deformation in a local coordinate system. To compensate for the distance between the global and local coordinate system, centrifugal and Coriolis terms must be taken into account. This leads to a non-constant mass matrix. The inertia forces get complex expressions, while the elastic forces are simple. FFRF are suitable for small-deformation and large-rotation analysis. Chamorro et al. (2011) use FFRF for simulation of railway tracks, which have similar geometry as a cable. According to Sun et al. (2018), only the Variable-domain Finite Element (VFE) variant of the FFRF, as presented in for example Horie et al. (2011), are good for MBS. The VFE cannot account for large deformations and large overall motion with variable-length bodies due to the inherent nature of FFRF.

6.2.6 | Geometrical Non-linear Beam Formulation (GNBF)

Jonker and Meijaard (2013) proposed the Geometrically Non-linear Beam Formulation (GNBF) for large deflection problems in analysis of flexible MBS. Timoshenko beam theory serves as the foundation for the deformation modes in the formulation. The beam is shear deformable. A cable is a very slender geometry, where shear forces could imperil the simulation of cables for errors. The GNBF is compared to several methods including the discrete deformation mode Bathe and Bolourchi (1979), geometrically exact formulations Romero (2008), natural coordinate formulation Avello et al. (1991) and a co-rotational formulation Crisfield (1990), where it shows good results. Compared to ANCF, see section 6.2.7, it is more accurate and less computational demanding. Romero (2008) points out that a geometrically exact formulation requires a special time stepping method. This makes the geometrically exact formulation more complicated to implement than ANCF elements.

6.2.7 | The Absolute Nodal Coordinate Formulation (ANCF)

For the last two decades, the Absolute Nodal Coordinate Formulation (ANCF) has gained attention for modelling of large-deformations and large-rotations in multibody dynamics, with simulation of tires and belt drives as examples, Shabana (2018). Shabana first proposed this element in 1996, Shabana (1997a). In contrast to FFRF, ANCF has a constant mass matrix, and no centrifugal and Coriolis forces. This makes it easy for the ANCF to solve accelerations, and continuity of the deformation gradient for dynamic simulations. ANCF elements use nodal displacements and slopes as DOFs instead of rotational parameters as in FFRF. Dibold et al. (2009) found that ANCF is less complicated and converges faster than FFRF in large deformations, especially with an increasing number of elements. Within the framework of ANCF, there are several element formulations, including special cable elements. A good overview of important features and applications of ANCF is given in, Gerstmayr et al. (2013) and Nachbagauer (2014). Nachbagauer address the differences between different ANCF elements. She ends up proposing what she sees as the most beneficial 3D ANCF element to use. Gerstmayr et al. (2016) presents ANCF elements with and without torsional stiffness, shear and cross section deformation. Bulín et al. (2017) presented a cable-pulley system where the cable was an ANCF element, and contact forces caused the pulley to rotate. A quadrosphere cable mechanism was simulated with this formulation with really promising results in Bulín et al. (2018). To simulate contact between the cable and the pulley there are different approaches. Westin and Irani (2017) developed a method for 2D cases with a large dynamic variation in the wrap angle and cable tension. It is common to use Hertz as the contact formulation, while Takehara et al. (2016) use Quinn method. Wang et al. has studied the contact between cable and cable with a continuous contact zone, where a master-slave technique has been used in Wang et al. (2014) and Wang et al. (2016).

6.2.8 | Arbitrary Lagrangian-Eulerian (ALE) - ANCF

The Arbitrary Lagrangian-Eulerian (ALE) formulation is combining the Lagrangian formulation and the Eulerian formulation, as the name suggests. In the Lagrangian formulation, the nodes in the FEM mesh and the material are attached to each other. This is the common formulation to use for simulation of structures. In the Eulerian formulation, the nodes in the FEM mesh are fixed in space and the material can flow trough. This is the common formulation to use for simulation of fluids. Hong and Ren (2011) proposed the ANCF in the framework of ALE, where the material could flow through the ANCF elements. Without the ALE formulation, the element would behave as a «regular» ANCF element. ALE opened up for the possibility to have stationary nodes around the pulleys, as illustrated in figure 10. The advantage being that fewer elements can represent the cable. The reason for this being that contact is numerically difficult to simulate, especially the moment contact occurs. When any random cable element can happen to be in contact with the pulley at some point of time, all the cable elements must be small. With ALE, free cable elements can be larger, allowing for fewer elements and faster simulations. Another advantage is that for simulation of reeling, it is possible to add or remove excessive cable. Based on Hong and Ren (2011), Peng et al. (2017a) came up with an ALE formulation for cable and pulley simulation handling variable cable length. A deployable mesh antenna was simulated for benchmarking in Peng et al. (2017b). Escalona (2017) discuss 1D, 2D and 3D ALE formulation with and without transverse deformation and twist. The ALE formulation is suitable for real time simulations, due to efficient calculations.

6.2.9 | Coupling Motion between Cable and Pulley

Qi et al. (2017) and Wang et al. (2017) points out that few studies propose a good formulation of coupling between cable and movable pulleys. Pulleys play an important role, with tensioning of the cable, and the flow of the cable relies on the

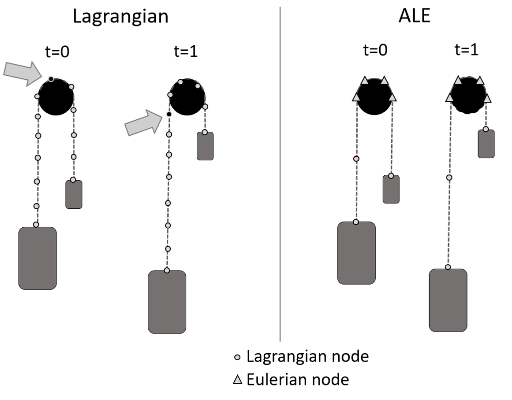

FIGURE 10 FEM model of an elevator mechanism with Lagrangian vs ALE formulation. The figure shows a cable pulled over a pulley with two masses attached, at two different time steps. A Lagrangian formulation requires many nodes to capture interaction between the cable and pulley; while an ALE formulation can have a high density of elements at the pulley, as they are stationary. This allows for fewer elements along the cable. The figure is based on figure in Escalona (2017).

rotation of the pulley. They proposed a formulation for dynamic analysis of flexible cables with time-varying length and coupling motions between cable and pulleys. The contact segment of the cable is moving together with the contact point on the pulley, with a shape constraint spatial description. Cubic spline interpolation is used to discretize the cable, which, can be regarded as an axially moving 1D-flow medium. The simulation include tensile strain, inertia and gravity forces of the cable, pulley and winches. The bending stiffness and torsional stiffness are neglected in this formulation, as flexible cables are easy to bend and twist. The papers presents examples of simulations of cable-pulley lifting systems of movable and fixed pulleys, with good results compared to ADAMS software simulations. There have not been other studies verifying the formulation.

6.3 | Evaluation of Alternatives

It is not straightforward to decide for the best alternative of a numerical formulation to use for cable and pulley simulation to implement in a DT of an offshore crane. There are many aspects to take into consideration like calculation time, dynamics and contact formulations. A table based on the subjective value method according Kossiakoff et al. (2011) are presented in figure 11. This was used for cross-referencing design requirements and options for evaluation of the different formulation candidates. Each of the criteria were weighted equally with the scoring from: 0 = not known, 1 = poor, 2 = fair, 3 = satisfactory, 4 = good, and 5 = superior.

For the alternatives of formulations for cable and pulley simulation evaluated in this paper the spring element is commonly used, but is lacking both a good dynamic representation and contact formulation. IGA are premature, as it is not FEM compatible, and the formulation is not extensively tested. It might be very relevant in the future. Dibold et al. (2009) found that ANCF converges faster than FFRF. ALE-ANCF has the highest score. It can represent contact between cable and pulley with stationary nodes, it allows for models with fewer elements and fast calculations. This makes it suitable for real time DTs. ALE-ANCF also allows for varying cable length. The Coupling Motion between Cable and Pulley is a promising method, with the second highest score. The method has a low score on reliability, as only one research group has publications on it. Even though the formulation seems promising, it should be used with care prior to further testing has been done.

	Design Requirements						
Formulations:	1. FEM Compatible	2. Dynamics	3. Contact	4. Calculation Speed	5. Time Varying Length	6. Reliability	SUM Results
Spring	5	1	1	5	3	4	19
IGA	1	4	2	0	0	2	9
The Bar Finite Element for Cable	5	3	2	4	0	2	16
A Parametric Super Element	5	1	1	4	1	1	13
FFRF	5	3	3	3	2	2	18
GNBF	5	3	0	4	0	2	14
ANCF	5	4	3	3	3	3	21
ALE-ANCF	5	4	4	4	5	4	26
Coupling Motion between Cable and Pulley	5	4	4	4	4	1	22

FIGURE 11 The alternatives for cable and pulley simulation evaluated according to the subjective value method, based on Kossiakoff et al. (2011), where 0 = not known, 1 = poor, 2 = fair, 3 = satisfactory, 4 = good, and 5 = superior.

7 | DECISION MAKING

DT applications in SE tend to focus on manufacturing or maintenance of objects, where this paper have pointed out the requirements to create a DT of an offshore crane for safer lifting operations. The DT should predict load movements, compensate with the control system, improve heave compensation, as well as monitoring for maintenance schemes. Identification of failure states and forecasting are important to prevent accidents. There are several challenges related to get a satisfactory functioning DT. Trough different cases, it was evident that simulations lacked a sufficient formulation for cable and pulley representation. A satisfactory cable and pulley simulation is critical for an operational FEA, used for a real time DT.

A trade study was performed to investigate alternatives for cable and pulley simulations. The numerical method ALE-ANCF had the highest score in the evaluation by the subjective value method. This method is very suitable for real time simulations due to relatively few elements needed, and that nodes can be stationary at contact areas with the pulley. It also has good dynamic representation of the cable, and can include contact as well as time varying length. ALE-ANCF is the recommended formulation to implement in a DT of an offshore crane.

SE have proven to be a useful approach for creation of a DT. Tools to expose lacks, setting design requirements and finding alternatives already have a framework ready to use. For structuring complex systems, this is invaluable. Since the creation of DT of offshore cranes have never been done before, SE is highly relevant.

8 | FURTHER WORK

- To verify the selected formulation for cable and pulley simulation, a DT of the laboratory knuckle boom crane should be made for benchmarking. This will verify if the selected alternative is feasible. Testing will also reveal further requirements for having a fully functioning DT of an offshore crane.

- A DT requires software for processing of sensor data, calculations, simulations and visualization. There are a large amount of software available, where some are specialized for certain tasks, while others are generalized. Further work involves investigation of software alternatives to use for a DT of an offshore crane.

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