

Trade study to select best alternative for cable and pulley simulation for cranes on offshore vessels

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Funding information

Norwegian Research Council, Grant/Award Number: 237896

Abstract

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 more complex and potentially dangerous. The use of digital twins (DTs) is emerging as one way to 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 toward the creation of a DT of cranes on offshore vessels. Several cases involving simulation of cranes revealed the lack of an adequate simulation of cable and pulleys suitable for use in a DT. The simulation is important for accurate results and for implementation in control systems. A trade study was performed to determine a numerical method adequate for cable and pulley simulation. The trade study identified the absolute nodal coordinate formulation in the framework of arbitrary Lagrangian–Eulerian as a promising numerical formulation.

KEYWORDS

cable, crane, digital twin, FEM, MBS, 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 complicate these operations. The recent trend has been to use smaller vessels, with larger cranes, as a means for saving costs. This makes the lifting operation more subject to instability due to the environmental excitations. A digital twin (DT) of an offshore crane supports a wide range of applications. It would allow for safer lifting operations with less downtime based on anticipated failure modes, such as buckling in bars and actuators, material yielding and fatigue predictions, as well as an improved control system. The DT simulations improve payload control allowing for lifting operations in demanding weather conditions, and better maintenance schemes based on fatigue predictions. If the control system detects irregularities, the operator is notified. In dangerous situations, the control system could restrict continuation of the operation. A DT could be used to estimate the weight of the payload, instead of using a scale, and the project manager could use data from the DT as basis for risk analysis when planning lifting operations.

A step toward creating a DT of a crane on offshore vessels is to improve the simulations. The Norwegian oil and gas industry relies heavily on offshore vessels with cranes, and the Research Council of Norway is currently funding this research through an innovation grant (SFI). This paper investigates the requirements for improved simulations as part of this research. 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 research. The main body of the paper then reports on requests for crane simulation according to cases and previous research. Here, it is observed that cable and pulley simulation lacks sufficient accuracy, and a better simulation of cable and pulleys is needed for 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 embed in a DT, where the real-time aspect is important. The paper concludes with a suggested cable and pulley simulation and further work. The paper follows the SPADE methodology as proposed by Haskins.¹

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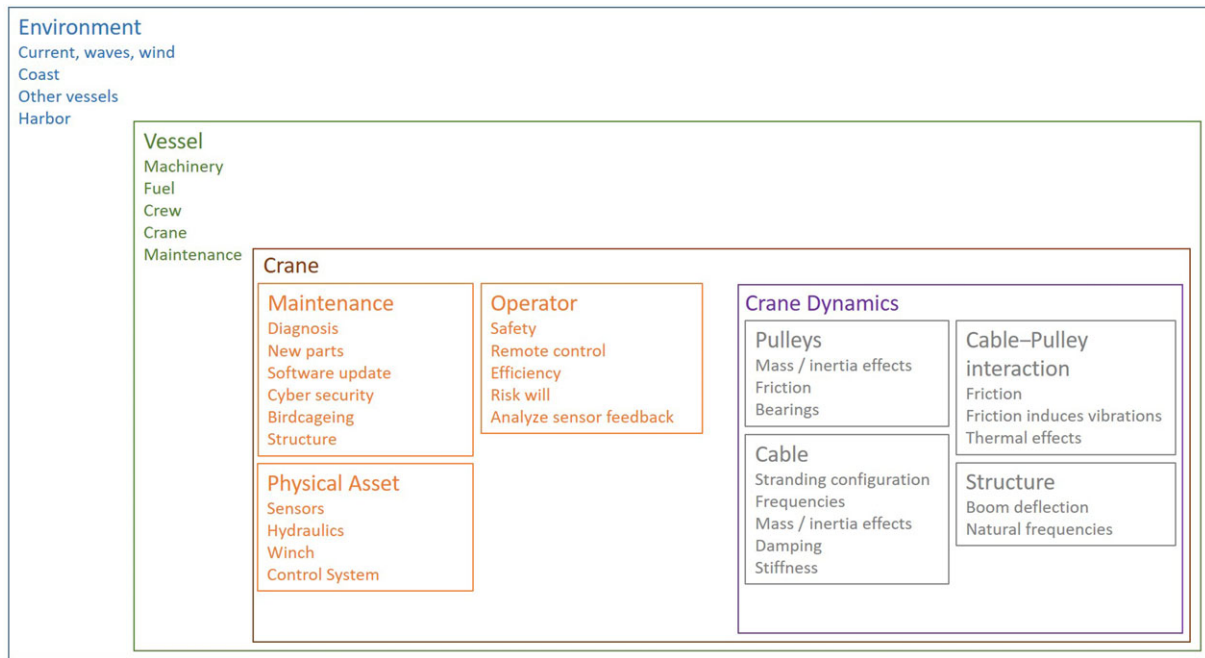


FIGURE 1 Context diagram for the crane dynamics of cable and pulleys

2 | BACKGROUND

Schluse and Rossmann² list several domains where the term “digital twin” is used differently for industrial practices: manufacturing flexibility, product design, maintenance, increased lifetime, testing, structural monitoring, performance efficiency, quality, and automation. A DT can be used, not only for engineering and manufacturing, but also operations and service. According to Boschert and Rosen,³ this implies that the DT could become a part of the real system, with actionable interactions. For the remainder of this paper, DT is defined as a digital copy of a physical asset, collecting real-time data from the asset and deriving information not being measured directly in the hardware.

The context diagram is a helpful tool to examine the systemic picture of what must be included to create a DT of an offshore crane, see Figure 1. The goal of a DT is to be able to simulate the whole crane system. The primary context for the DT is crane dynamics, which is an attribute of the crane, both the physical asset and its maintenance and operation. These in turn are mounted on a vessel that operates in maritime environments, including both open water and harbor operations. The way these elements interact during a lifting operation is described here.

The winch on 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 a better control system. The control system includes heave and sway compensation and detection of critical loading conditions. The heave compensation maintains the payload motionless with regard to the seabed or other vessels. The anti-sway prevents the payload from swinging. For lifting operations involving other vessels, the vessels will be in different swing phases. Tordal et al⁴ has proposed a method for vessel to vessel operations, where a motion reference unit is placed in

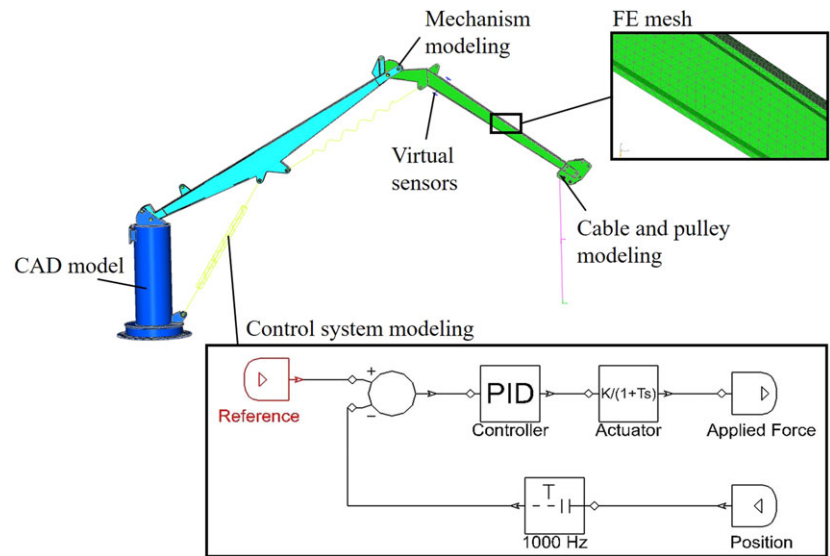
each vessel allowing for an accurate and reliable relative motion estimate. Critical loading conditions causing severe instability and rolling in the vessel should be detected and handled by the control system.

The context diagram highlights that crane dynamics are influenced by the cable and pulleys. The control system would benefit from simulations running in the DT that provide additional input data, such as the time delays caused by the hydraulics of the crane. This includes other factors of crane dynamics, such as ways the boom deflects, pulleys, bearings, inertia effects, friction, and damping. The frequency on the bearings could be influential when it comes to decoupling the crane for simulation, without significant loss of accuracy. 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 frequencies or vibrations in the cable are relevant inputs for the control system. The frequencies are influenced by the loading conditions and the length of the cable. Cables can withstand large axial loads in comparison to bending, compression, and torsional loads. For lifting operation with long cable spans, the elongation of the cable cannot be neglected. The cable pulley interaction is important, where contact and friction have to be defined.

Likewise, maintenance is a critical factor for the crane to be operational and is important when planning, to minimize downtime. A functioning DT requires the physical crane to be equipped with weather-resistant sensors, placed where they are shielded from the environment.

A multibody system (MBS) consists of several submodels, which make up the system being simulated, see Figure 2. The different parts have a computer aided design (CAD) model, which could be used as a rigid body, or meshed with finite elements for elastic behavior. Mechanism modeling uses joints to connect the parts for interaction. Control system modeling is used for actuators, such as the hydraulic cylinders

FIGURE 2 A CAD model of the crane system with different submodeling elements indicated



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 modeling is usually simplified to an axial spring.

Finite element analysis (FEA) 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 step 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. The DT on the other hand takes in real-time sensor data and updates the simulation, as it steps through time. This gives the engineer a much better insight into what is happening, and this real-time aspect requires fast calculations. Therefore, the purpose of FEA in an operational mode is 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. Hong et al.⁵ remark that 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. FEM works by dividing the 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 describe the behavior of the elements, and how they interact with each other during the simulation. There are numerous element types, specialized for different simulation tasks.

A simple example of a DT is found in Figure 3. In this illustration, the physical sensor data (PSD) from the physical crane are stored in a state vector, which contains stroke length of actuators, turn angle, reference strain for verification and calibration, and applied load from the payload at the crane tip.

$$PSD(t) = [\Delta L1, \Delta L2, \Delta \theta, \epsilon_{ref}, \epsilon_{temp}, mg]$$

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 actuators are measuring stroke length, the reaction forces can be found in the digital actuators.

The strain history can be found for any part of the crane, by virtual sensors. This is relevant for detecting fatigue failure. It is important to cross check and recalibrate the DT to avoid divergence from the physical crane over time. The virtual strains are verified by comparison with reference strains from strain gauges placed at hot spots. For offshore cranes, the strain gauges have to be carefully placed and shielded from the harsh environment. Drifting in strain gauges is inevitable, for example, where the temperature is fluctuating. A strain gauge is placed at an untensioned part of the crane, as a reference for temperature. Filtering sensor noise is important to handle drifting in sensors. When starting the DT, both the DT and the physical crane should be in a preset zero position. Direction and size of forces are relevant for detecting stability issues and critical loading conditions. 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 and sent to the cloud.

$$DSD(t) = [F1, F2, M, \epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4]$$

The data in the cloud could be used further for visualization and presentation of results. The weather and wave forecast are additional data relevant to store in the server cloud, for risk analysis of the job.

In the video posted by Raftery,⁶ 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 indicate the stress level in the beam. The stress is a consequence of the force applied by the hand. The inverse method refers to the numerical equations in a simulation, where the input data are a measured value,

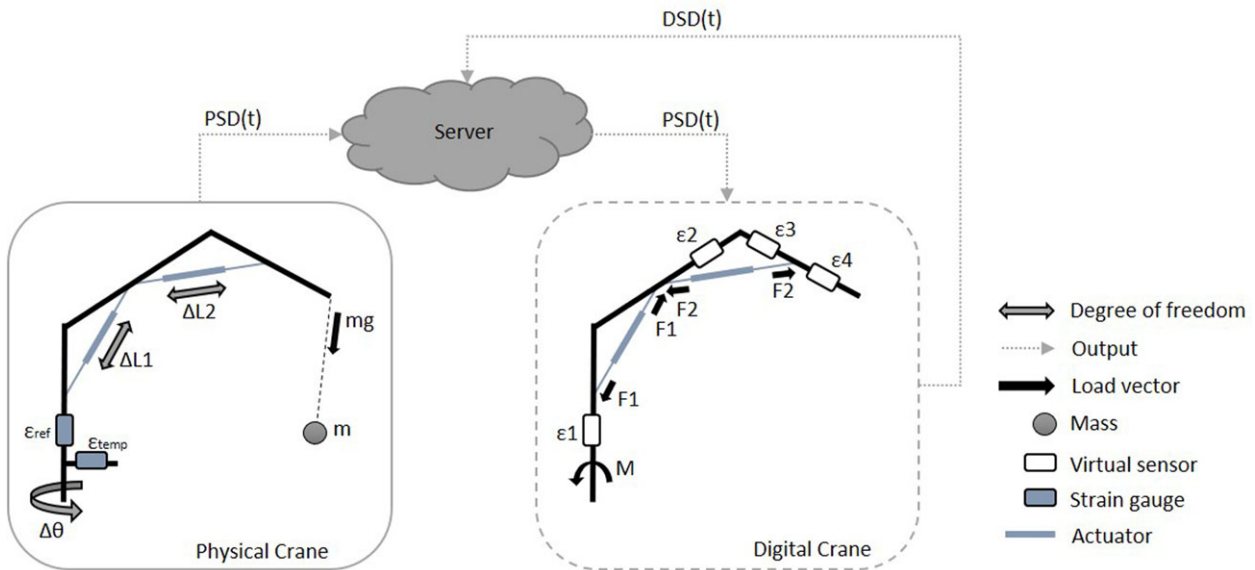


FIGURE 3 Sensors on the physical crane send real-time collected data to the DT. By the inverse method, the DT distributes the inputs to virtual sensors

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 loading conditions, to predict the structural integrity. Solvers must 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 is 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, helps 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 increases the possibility of making good decisions, exposing gaps, problem solving, and making progress with confidence. Systems engineering (SE) provides tools to handle this. Creating 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.

The SPADE methodology was introduced by Haskins,¹ see Figure 4, and was used as the research method in this paper. SPADE is an acronym constructed from the words: stakeholders, problem formulation, 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 updates the old findings with 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 identified early in the design process. During

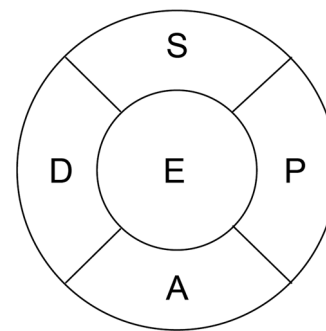


FIGURE 4 “SPADE methodology/framework graphical representation”¹

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 formulation stage exposes deficiencies in existing technology for the creation of a DT of an offshore crane. Based on these deficiencies, different solutions are compared in the alternatives stage. To evaluate and compare alternatives for a numerical formulation for cable and pulley simulation, the tradeoff analysis tool based on Blanchard and Fabrycky⁷ 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.⁸ The subjective value method weights the characteristics of each formulation against each other to find the one that best suits the system as a whole, according to design requirements. The score assigned was based on papers describing the features. Extensive testing of all the alternatives for cable and pulley simulation would be inadequate due to time limitations, making the trade study a more suitable process. Making a qualified decision based on available information allows 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.

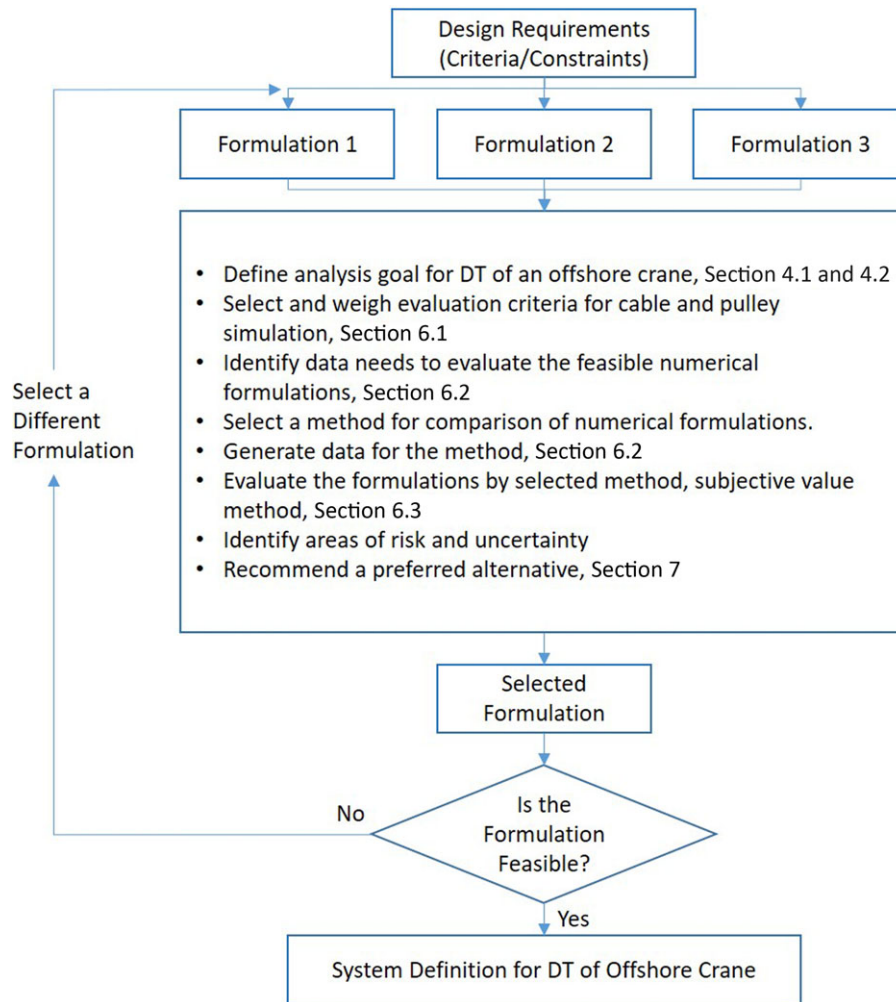


FIGURE 5 Trade-off analysis process, based on Blanchard and Fabrycky⁷

4 | IDENTIFICATION OF SYSTEM STAKEHOLDERS AND NEEDS

Grieves and Vickers⁹ cite siloing, (lack of) knowledge of the physical world, and the number of possible states that a system can take as the main challenges for a DT. Siloing refers to lack of communication between the different groups working on the same project. The issue of siloing is addressed by identifying the stakeholders and involving them in the project. A stakeholder is defined by Freeman¹⁰ as “any group or individual who can affect or is affected by the achievement of the organization’s objectives.”¹⁰ (p. 46)

As previously mentioned, SFI Offshore Mechatronics functions as a bridge for knowledge flow between academia and industry. The project goal is to strengthen competitiveness and innovation capacity in Norway. This research is part of a project with a stated 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.” The project has the following partners:

Academic Partners:

- Aalborg University
- NORCE (Research Institute)
- NTNU (Trondheim and Aalesund)
- RWTH Aachen
- University of Agder

Industry Partners:

- ABB
- Bosch Rexroth
- Cameron
- Egde Consulting
- GCE NODE (Cluster)
- Klüber Lubrication
- Lundin Norway
- MacGregor
- MHWirth
- National Oilwell Varco
- Skeie Technology
- Stepchange

Partners meet regularly, and industry partners make themselves available to academic researchers. Figure 6 summarizes the needs of the stakeholders for this research.

- SFI crane producer partners are interested in making safe and reliable products. Improved simulations of cranes as well as real-time feedback would help them to understand how forces acts on the

Stakeholders		
Group:	Who:	Needs:
Primary	The Research Council of Norway	Strengthen competitiveness and innovation capacity in Norway
	SFI Partner Crane producers	Improved simulations
Secondary	Vessel manufacturers	Flexible solutions
	Vessel owners	Ships capable of multiple operations
	Operators of cranes	Safer lifting operations
Tertiary	Software companies	Improving their capability for solving more intricate problems
	Producers of sensors	How their equipment is used
	Other industries	New technology they could benefit from

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

crane during operation. This would be valuable insight for technical upgrades, which are usually based on what the vessel manufacturers and owners request for the products.

- Vessel manufactures are interested in installing the most suitable crane for the vessels. They are also interested in flexible solutions, which provide a competitive advantage.
- Vessel owners want vessels capable of multiple operations, because laid-up vessels are very costly. This also implies using the right equipment for the job, with the lowest cost. Improved simulation allows for better planning of the operation, as well as better planning of maintenance work.
- Operators of cranes want reliable controls and safer lifting operations. Increased automation and improved control systems, where real-time feedback is important, means that the operations become easier with improved payload control, vessel to vessel transfers, and heave compensation.
- Software companies specializing in simulation and analysis of problems concerning failure assessment, fracture, and fatigue are interested in improving and expanding their capability to provide accurate and fast calculations for solving intricate problems.
- Producers of sensors and monitoring equipment for physical assets are interested in the ways their equipment is used by the industry and how the data collected are applied in simulations.
- Other industries could benefit from new technology developed for offshore cranes. Elevators, draw works, power-lines, and robotics are examples of applications with similar challenges involving cable and pulley simulation.

4.1 | Measures of effectiveness

When the problem has been formulated, then criteria are put in correct term as measures of effectiveness (MOE). MOE represent the viewpoint of stakeholders and Sproles¹¹ argues that it assists in making the right choices based on the stakeholders' needs. This establishes the success criteria to recognize when the end goal is reached. MOE for this project:

- A cable and pulley simulation that improves the overall real-time simulation of a crane on an offshore vessel.

- A cable and pulley simulation that can be integrated with DT of a crane on an offshore vessel.

4.2 | Technical performance measures

Technical performance measures (TPMs) are key goals to be met, where the actual progress of technical achievement is monitored using periodic measures or tests. As noted by Garvey and Chien-Ching,¹² this will indicate how well a system is approaching its performance requirements. The TPMs for this project include:

- Less unplanned downtime: Due to better prediction of equipment failure, the crane can be maintained prior to breakdown.
- Less downtime: Maintenance is performed when required, instead of on a predetermined schedule.
- Less maintenance cost: Only the worn-out parts are replaced, leading to a longer lifetime of crane and parts.
- Less waste: As the crane and the parts are in service for a longer period, there will be less waste.
- Fewer incidents: The number of industrial injuries concerning work with cranes on offshore vessels is reduced when using a DT. The DT has alarm systems for dangerous situations and has improved payload control.
- Faster operations: With better payload control, the lifting operations will be carried out more efficiently.
- Increased operational time: Due to a better control system, work can be done in harsher environments.

Most of these measures have a temporal quality, which means that the researcher must rely on historical data and data collected after the DT is implemented to assess the actual benefits of the DT, and then the simulation. However, some practical assertions regarding increased operational time and maintenance can be estimated.

5 | PROBLEM FORMULATION

Over the past 40 years, there have been several studies concerning simulation of offshore cranes, where, for example, Strengehagen and Gran¹³ investigated the dynamic response and fatigue life of offshore

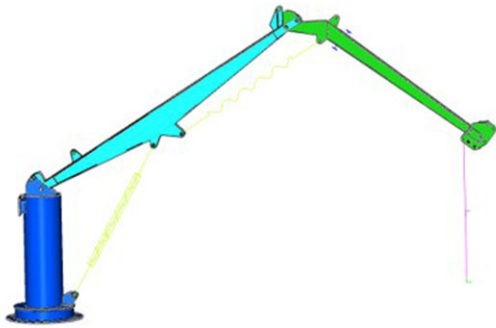


FIGURE 7 Laboratory crane 1 is a knuckle boom crane built in one of the laboratories at NTNU, with a detailed FEM model of the crane

cranes over 30 years ago. 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.”¹³ (p. 520). Compression forces in ropes and cables will only cause them to fold, not take up any significant force. Langen et al¹⁴ published work concerning the dynamic behavior of an offshore crane. Their goal was design verification against overload and fatigue. The cables in the simulation were represented as axial springs. Ku and Roh¹⁵ and Hong et al⁵ are more recent studies concerning offshore cranes. The first investigates the safety of installation of offshore wind turbines by floating cranes. This is done by simulation with wind, hydrostatic, and dynamic forces acting on the crane. The second predicts dynamic loads on a crane on an offshore support vessel. It argues for the importance of using a flexible body model, rather than a rigid body, as the boom flexes. Research addressing coupling motions between crane and vessel, ways external forces act on the crane structure, ways the boom flexes, and the location of hot spots for stress, is well documented. The matter of simulating MBS assembled with cable and pulleys, such as cranes, has been simplified over time, hence the need for more advanced and accurate cable and pulley simulation has emerged. Moseid¹⁶ started this work by introducing several challenges related to two-dimensional finite element-based modeling of cable and pulley systems, such as inherent dynamics and friction effects. This project seeks to develop a cable and pulley simulation capable of real-time structural monitoring and improved payload control for cranes on offshore vessels.

The fact that cable and pulley simulation is needed is also evident in the following cases from Fedem Technology and NTNU sources, presented in the next sections, where there are different types of cranes investigated, and the objectives of the simulations vary. They have in common that they would benefit from an improved cable and pulley simulation. The cases exposed the need for an improved cable and pulley simulation and 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

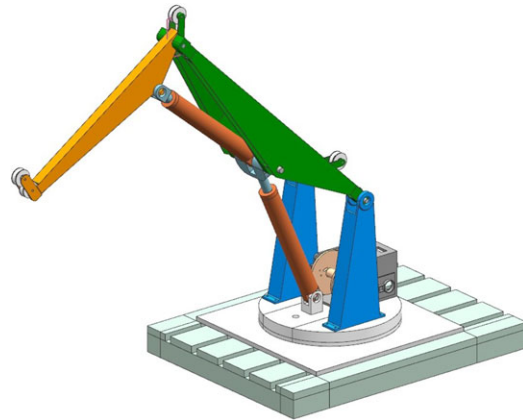


FIGURE 8 Laboratory crane 2 is a knuckle boom crane for testing in a wave pool

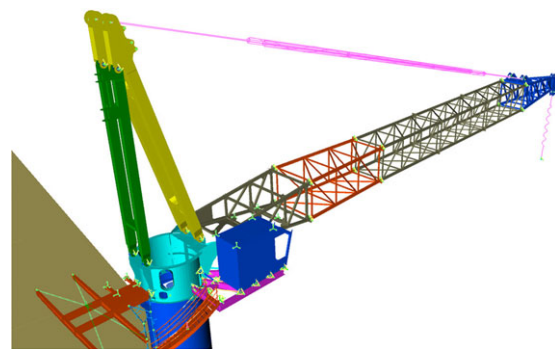


FIGURE 9 Tower crane installed on the oil rig Johan Sverdrup

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 conditions during lifting operations, structural integrity calculations, fatigue life prediction, and stability monitoring. Insight gained here could be used for condition-based maintenance.

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 how the vessel movements affect the lifting operation, and what response this will have in the crane and the payload. The hydrodynamics must be included in the simulation. Studies conducted with this crane can help uncover and assess critical conditions for when the system becomes unstable. The main factors influencing stability are critical payloads, wave and wind conditions, and active damping.

5.3 | Johan Sverdrup - tower crane

Structural vibrations in the tower cranes on the recently deployed oil rig Johan Sverdrup have 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 delays related to boom flex, hydraulics, and tension in the cable. Since the

frequency in the cable changes with varying length, mass, and stiffness in the cable, an improved cable and pulley simulation could make the overall results more accurate for this case.

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 Fabrycky⁷ has been performed, see Figure 5. The main intention for this project is to improve the overall behavior of a crane. To include internal effects in the cable, such as interaction between the strides, demand additional computing power. This could jeopardize the real-time aspect for a DT, where dynamics are of main interest. For offshore cranes, the demands for dynamics are set higher than for onshore cranes with less platform movement. 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 winch stops 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 can have severe consequences. 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. This implies that the formulation must handle different simulation scenarios. If the control system fails, the crane could suddenly drop the payload, jerk the payload, or stop running. Tested formulations known to be stable and robust should be used to prevent this. Design requirements for a numerical formulation of a cable and pulley simulation follow 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. The simulation method should include dynamics in the cable, where mass, damping, stiffness, and inertia effects are included. This is important for prediction of reaction forces and position of a cable in motion.
3. The simulation method should include contact and friction between cable and pulley, and between different cable segments.
4. The simulation method should perform with acceptable computational speed, to accommodate the real-time aspect of a DT.
5. The simulation method should compute varying cable length over time, with mass updated accordingly. This is important for correct axial stiffness for applications, where the cable is lowered or elevated.
6. The simulation method should result in reliable numerical formulation with documentation as evidence of extensive testing.

6.2 | Alternatives for cable and pulley simulation

Based on the MOE, stakeholders, and design requirements, alternatives for cable and pulley simulation are identified and briefly described in the following sections.

6.2.1 | Spring

In FEA, a cable has commonly been represented as an axial spring.^{14,17} This is derived from Hooke's law, $F = -kx$, 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 pulleys are 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

Raknes et al¹⁸ use isogeometric analysis (IGA) to describe large deformations in a 3D cable. Ribs of an umbrella and bow and arrow are numerical examples tested. Thai et al¹⁹ published a paper concerning static application of cables with IGA. The textbook by Cottrell et al describes IGA, and in chapter 3 it is presented 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 interact, but it would be challenging in more advanced models where nodes in the mesh and CAD geometry do not necessarily coexist and merge. IGA still suffers from some numerical challenges, and the major drawback is that it struggles to handle contact analysis.²¹ The use of IGA would involve a risk, as the numerical formulation is less mature than FEM, and possess possible complications when combining it with FEA.

6.2.3 | The bar finite element for cable

The bar finite element²² is based on a principle to split the bar element into perfectly straight and homogeneous elements. The elements have elastic properties without rotational degrees of freedom (DOF). Through 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 number of elements are 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 Choo²³ present a super element numerical formulation for a cable passing through several pulleys. The method can represent complex geometric paths for a long cable. A tower crane has been analyzed by this formulation. Static simulations are the primary target for this formulation; therefore, it neglects the dynamic behavior of the pulley.

6.2.5 | The floating frame of reference formulation

Floating frame of reference formulation (FFRF) was the most widely used formulation for simulation of flexible MBS.²⁴ 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 is described in a local coordinate

system. To compensate for the distance between the global and local coordinate system, centrifugal and Coriolis terms must be considered. This leads to a nonconstant mass matrix. The inertia forces become complex expressions, while the elastic forces are simple. FFRF is suitable for small-deformation and large-rotation analysis. Chamorro et al²⁵ use FFRF for simulation of railway tracks, which have similar geometry as a cable. Only the variable-domain finite element (VFE) variant of the FFRF, as presented in, for example, Horie et al,²⁶ is good for MBS.²⁷ 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 nonlinear beam formulation

Jonker and Meijaard²⁸ proposed the geometrically nonlinear 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 by Bathe and Bolourchi,²⁹ geometrically exact formulations by Romero,³⁰ natural coordinate formulation by Avello et al,³¹ and a corotational formulation by Crisfield,³² against which GNBF shows good results. Compared to absolute nodal coordinate formulation (ANCF), see Section 6.2.7, it is more accurate and less computationally demanding. Romero³⁰ 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.

6.2.7 | The absolute nodal coordinate formulation

For the last two decades, the ANCF has gained attention for modeling of large-deformations and large-rotations in multibody dynamics, with simulation of tires and belt drives as examples.³³ Shabana³⁴ was the first to propose this element. In contrast to FFRF, ANCF has a constant mass matrix, and no centrifugal and Coriolis forces. This makes it relatively easy for the ANCF to solve accelerations, and continuity of the deformation gradient for dynamic simulations. ANCF elements use nodal displacements and slopes as DOF instead of rotational parameters as in FFRF. Dibold et al³⁵ 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 al³⁶ and Nachbagauer.³⁷ Nachbagauer addresses the differences between different ANCF elements. She ends up proposing what she sees as the most beneficial 3D ANCF element to use. Gerstmayr et al³⁸ present ANCF elements with and without torsional stiffness, shear, and cross section deformation. Bulin et al³⁹ 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 promising results.⁴⁰ There are different approaches to simulate contact between

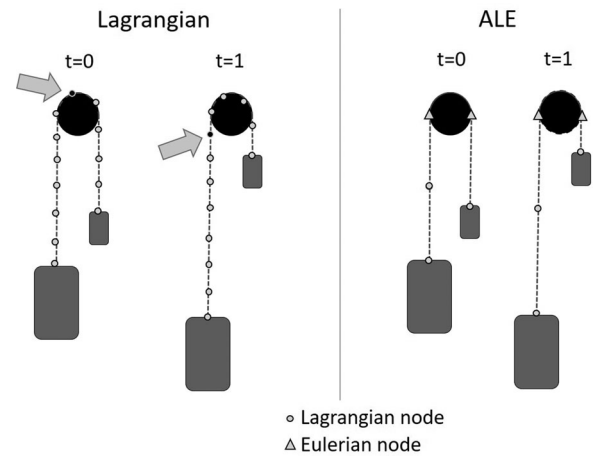


FIGURE 10 FEM model of an elevator mechanism with Lagrangian versus ALE formulation. The figure shows a cable pulled over a pulley with two masses attached, at two different time steps. A Lagrangian formulation requires many nodes to capture interaction between the cable and pulley; while an ALE formulation 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 by Escalona⁴⁸

the cable and the pulley. Westin and Irani⁴¹ 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 al⁴² use Quinn method. Wang et al⁴³ studied the contact between cables, and narrowed it down to a cable with continuous contact zone.⁴⁴ Both studies used a master-slave technique.

6.2.8 | Arbitrary Lagrangian–Eulerian - ANCF

The arbitrary Lagrangian–Eulerian (ALE) formulation combines the Lagrangian and the Eulerian formulations, 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 through it. This is the common formulation to use for simulation of fluids. Hong and Ren⁴⁵ 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 possibility to have stationary nodes around the pulleys, as illustrated in Figure 10. The advantage being that fewer elements are needed to represent the cable. The reason for this is that contact is numerically difficult to simulate, especially for the timesteps when contact between elements occur during a simulation. 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 the simulation of reeling, it is possible to add or remove excessive cable. Based on Hong and Ren,⁴⁵ Peng et al⁴⁶ came up with an ALE formulation for cable and pulley simulation handling variable cable length. A deployable mesh antenna was simulated for benchmarking.⁴⁷

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,⁸ where 0 = not known, 1 = poor, 2 = fair, 3 = satisfactory, 4 = good, and 5 = superior

Escalona⁴⁸ discusses 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 al⁴⁹ and Wang et al⁵⁰ point 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 rotation of the pulley. A numerical formulation for dynamic analysis of flexible cables with time-varying length and coupling motions between cable and pulleys was proposed. The contact segment of the cable moves 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 includes tensile strain, inertia, and gravitational forces of the cable and pulleys. The bending stiffness and torsional stiffness are neglected in this formulation, as flexible cables are easy to bend and twist. The papers present examples of simulations of cable-pulley lifting systems of movable and fixed pulleys, with good results when compared to simulations done in the ADAMS software. There have not been other studies verifying the formulation.

6.3 | Evaluation of alternatives

It is not straightforward to decide upon the best alternative for a numerical formulation to use for cable and pulley simulation. There are many aspects to take into consideration, such as calculation time, dynamics, and contact formulations. An analysis based on the subjective value method according to Kossiakoff et al⁸ is 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 was weighted equally with the scoring from: 0 = not known, 1 = poor, 2 = fair, 3 = satisfactory, 4 = good, and 5 = superior.

Based on the alternatives of numerical 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 is premature, as it is not FEM compatible, and the formulation is not extensively tested, although it might be relevant in the future. ANCF converges faster than FFRF.³⁵ 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 until further testing has been done.

7 | CONCLUSIONS

Decision making is the fourth element of SPADE. 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 since few elements are needed, and the 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.

DT applications in SE tend to focus on manufacturing, whereas this paper has focused on maintenance and real-time operations of an offshore crane. Requirements to create a DT of an offshore crane for safer lifting operations with less downtime have been addressed. Improved fatigue predictions allow for less downtime due to better planning of maintenance. An improved control system makes the lifting operations safer with detection and alarming of critical loading conditions and improved payload control. It also leads to less downtime as lifting operations can take place in harsher environments. There are several challenges related to achieving a satisfactory functioning DT. Through different cases, it was evident that simulations lacked a sufficiently

robust numerical formulation for cable and pulley representation. A satisfactory cable and pulley simulation is essential for an operational FEA, used for a real-time DT.

SE has proven to be a useful approach for the creation of a DT, because it provides a ready-made framework with tools to expose deficiencies, establish design requirements, and find alternatives. For structuring complex systems, this is invaluable. Since the creation of DT of offshore cranes has never been done before, SE is highly relevant.

8 | FURTHER WORK

This paper documents the process of choosing a numerical formulation method. It remains now to move to the next phases as follows:

- 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 is a large selection of software available, where some are specialized for certain tasks, while others are generalized. Further work involves the investigation of software alternatives to use for a DT of an offshore crane.

ACKNOWLEDGMENTS

The research presented in this paper has received funding from the Research Council of Norway, SFI Offshore Mechatronics, project number 237896. Thanks to Industry Partners for sharing their needs for the DT, and to the anonymous reviewers whose suggestions helped improve this paper.

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How to cite this article: Fotland G, Haskins C, Rølvåg T. Trade study to select best alternative for cable and pulley simulation for cranes on offshore vessels. *Systems Engineering.* 2019;1–12. <https://doi.org/10.1002/sys.21503>