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Virtual prototyping of offshore operations: a review

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ABSTRACT
Virtual prototyping of offshore operations (VPOO) is performed to plan and validate planning of infrequent or demanding operations characterized by high risk and low margins of error in hostile and remote environments distant from emergency response bases that require expensive equipment. Key elements of VPOO is the rapidity of virtual prototyping and the human-centric approach necessitating high quality visuals and real-time time-domain simulation. This survey reviews publications, commercial software and simulators, and regulations on offshore operations. Findings indicate that the VPOO is not common in the industry, offshore operation regulations lag behind the state of the art in industry in terms of mission planning, and this field has been subject to scarce commercial and scientific scrutiny so far. A discussion of future developments and trends concludes the paper.

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Virtual prototyping; operation planning; human-in-the-Loop; hardware-in-the-Loop; real time simulation; offshore operation

1. Introduction

Offshore operations are infrequent transformational activities performed during offshore campaigns, including, but not limited to, installing or decommissioning subsea equipment, replacing and tying-in umbilicals and pipes, deploying seismic streamers. For the sake of readability, we use offshore operations for offshore marine weather-restricted operations in sense of Det Norske Veritas Germanischer Lloyd (DNVGL) Offshore Standards (DNV 2011). Offshore operations are characterized by their complexity, interdisciplinarity, hostile environments, advanced equipment, low level of standardization, farness from emergency response. One could argue that Anchor Handling (AH) operations are advanced and perilous maritime operations, they comply with all the previous criteria but low level of standardization of the equipment, and are therefore excluded from the operations in this study. More often than not, offshore operations represent a small but critical part of the life cycle of an overarching engineering project lasting over decades and their planning of the operations depends on the changes in the design of the parent project in terms of equipment to installation and location.

Properly planning offshore operations is critical to mitigating human and financial risks as it is crucial to identifying unworkable, inconsistent, or incomplete procedures early at design and engineering level before they are performed offshore. For this purpose, during the planning phase, it is important to identify the limiting factors, the operation's non-accidental critical factors which will stop the operation: human motion sickness, DP-capability of the ship, maximum roll and pitch handled by a crane system, maximum significant wave height supported by an anti-heave control system etc. Another key element of the planning analysis is the determination of the weather window, which is the time period during which an offshore operation can be safely commenced and completed. The period depends on the weather conditions, as operations in calm weather tend to be performed faster than in harsher conditions and on the reliability of weather reports. Contractors and operators typically aim at increasing the weather window to maximize the capacity of the chartered offshore operation vessels. The following section gives an overview of the offshore industries requiring offshore operations.

Each operation has its own characteristics and the suitability of the practices and methods highlighted might not be generalized. However, VPOO is a tool designed to handle novelty and to reduce risks by testing solutions before the start of operations. The Åsgard subsea compressor installed by Equinor (Time and Torpe 2016) is one working example as the commissioning procedures were validated during real-time simulation at OSC (Offshore Simulator Centre) in a virtual prototyped session involving a full offshore crew of 100.

1.1. Virtual prototyping of offshore operations (VPOO)

Wang (2003) describes virtual prototypes (VPs) as Q2 'computer simulation[s] of a physical product that can be presented, analyzed, and tested from concerned product life-cycle aspects such as design/

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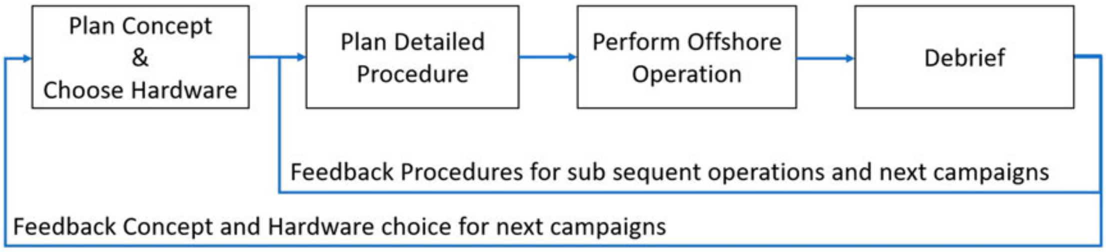

Figure 1. Conventional Offshore Operation Design.

engineering, manufacturing, service, and recycling as if on a real physical model.' In the context of offshore operations, VP refers to Simulation-Based Mission Planning. VPOO uses VP models, 3D visual models connected to physical properties, of the offshore equipment.

Operational procedures are normally designed and presented on A4 reports or slides, often with 2D drawings of the objects to install, sometimes with animations showing the sequence of activities. While animations are a powerful tool for rapid conceptualization of operational procedures, they do not identify possible static clashes, such as when a new part does not fit in its designated area, or dynamical clashes that arise during installation, such as when the planned path is unworkable. Examples from the industry count cranes in the way of cantilever, beams in the way of a retrofit balcony, winches working over their maximum speed or their Working Load Limits (WLL) or Safe Working Load (SWL) or even Ultimate Working Capacity (UWC) or equipment clashing with installation. Simulating the operation in a physics-based simulator enables the discovery of 'bad surprises' through identifying completeness and consistency of the procedure, the clearances, the reachability of the tools, and feasibility of operation early in the engineering stage.

The above-mentioned planning errors seem to be systemic: engineering teams tend to operate and think in silos and do not consider the system outside the boundaries of their mandate and mastery. This is the case when parallel engineering teams have closed development loops. A holistic approach of operations to plan for the best and the worst case scenarios is thus necessary. It is important to consider the interactions between the different components of the system throughout the lifetime of a engineering project planning, especially when the systems and subsystems are changed, improved, and versioned independently. Furthermore, it is both expensive and impractical to gather skilled workers in a real-world environment, it is rather adequately done in a virtual one (Håvold et al. 2015), in which the environmental conditions are deterministically reproducible and the consequences of a crash or failure are non-critical.

Finally, Pan and Hildre (2018) mention the need designers and engineers have to access *in situ* behaviour during offshore operations. Offshore crews are composed of interdisciplinary personnel with different educational and social backgrounds and very often with cultural and linguistic barriers. Inadequate professional training and experience, heavy cognitive workloads and stress, human miscommunication, inappropriate team organization, and misconceptions about machine functionalities are frequent causes of accidents in operations. Human factors are a major cause of incidents in the maritime industry (Baker and McCafferty 2005; Allianz Global Corporate & Specialty 2019) and offshore production (Gordon et al. 1996; Zhen et al. 2020). The offshore operations we describe in this article are classified between marine operations and offshore production; human factors nevertheless play a major role in the success or failure of the operation. For the period 2011–2016, the European Maritime Safety Agency (EMSA) reported that 'human erroneous action' is the root cause of accidental events in 60.5 % of the cases over that period, and 72.7% as contributing factor (EMSA 2017). This stresses the relevance of operational planning and training in a VP simulation, as it places the different operational activities in their sociotechnical context and enables its holistic safety (Pan and Hildre 2018) and performance analysis.

Figure 1 shows a typical subsea operation design process without VP. The high-level planning and selection of equipment such as vessel type and crane specs are performed by the operator and contractors during the tender phase. Once the contract between the selected contractor and operator is in place, the Front-End Engineering Design (FEED) will be performed, followed by marine operations engineering: calculations and measurements, such as towing tank tests, and calculation of weather window, maximum wind, or significant wave height. The results will form the foundation for the detailed procedures. Once the operation is performed offshore, debrief and feedback on experience can be performed to improve the planning of the subsequent operational campaigns (Time and Torpe 2016). The feedback loop is thus not immediate, leading to loss of information or irrelevant context.

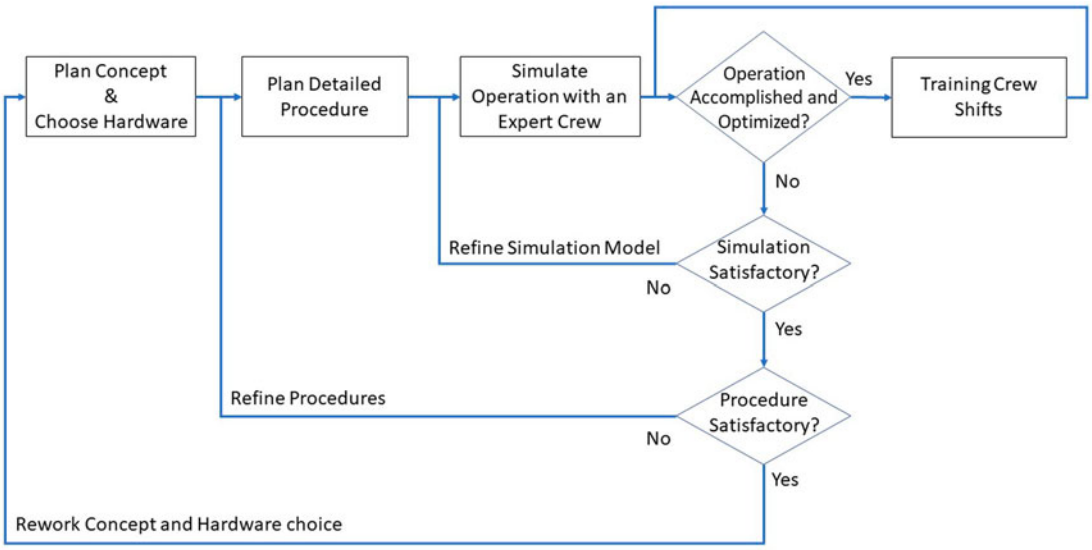

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Figure 2. Iterative Offshore Operation Design with VP.

The flow chart depicted in Figure 2 shows the design process of an operation procedure with VP at an early stage of the engineering phase, after the engineering calculations and the procedures have been designed. The flow chart shows four feedback loops originating from the simulation and training evaluations. The first loop addresses the quality of the simulation itself, for which one has to improve the model and simulation if necessary. The second is the refinement of the procedures, in case the simulation run would prove them incomplete or unworkable. The third loop addresses the unworkability, the show-stoppers, of the operation, which arise due to inadequate equipment or impractical concept. This implies that the design is not frozen in that early stage; instead it should be receptive to changes due to risks identified during simulation. Section 7 will elaborate an optimization possibility. The figure shows two simulation phases: one with an expert crew and one training phase with all offshore shift personnel. The former is in the inner loop for fast iterations. The latter is in the outer loop and serves two purposes: to train all the crew shifts and to provide management human factor feedback (communication, organization, stress etc.) on the operations and make procedural adjustments based on the corresponding risk assessment. Such assessments might prioritize enlarging the weather window, averting human overload, or considering energy efficiency and low environmental impact (NOx, SOx, CO_2, noise, etc.) of the operations, as described in Major et al. (2019).

Once any negative outcomes are discovered, the operation can be redesigned and procedures updated. VPOO is thus an iterative process. At the end each iteration, feedback addresses the refining of the procedure and the simulation.

VPOO involves training experts for a particular operation: not teaching marine officers, ROV pilots, or crane drivers how to do their jobs, but, rather, teaching the engineers how the operation can be performed in real life and sharpening the team members' role in the operation. Because VPOO is in essence an open-ended training, once the operational procedures are established and optimized, they can be trained for in the same simulator. This method is valid for contingency planning (*what-if* scenarios), where power shortages leading to vessel drift off, crane malfunction, etc. (DNV 2014) are planned.

1.2. Virtual prototyping compared with other methods

In offshore operation planning, engineering simulation is the method of choice, but animation, training in simulator, and virtual prototyping are also useful tools. Table 1 lists the different methods and their main traits. Campaign planning tools are included, even if they do not represent a VP as such, they often provide probability-based simulation and optimization of activity. The comparison criteria and terminology are explained in later sections. In a conventional planning process, early in the project, animations are created to rapid prototype the operation, sometimes in parallel with engineering. The procedures are then trained on in the full mission simulator, when engineers train marine and offshore personnel on the operational procedures. VPOO overlaps the various phases by providing an engineering and training platform.

2. Overview of offshore operations and their requirement for virtual prototyping

In this section, we analyse the needs of each type of offshore operation and explain the similarities between seemingly different industries. Offshore

Table 1. Comparison of VP with other technologies.

Technology	Purpose	Pros	Cons
Campaign Planning Tools	Campaign Optimization and Planning	Give an overview Coordinate between contractors Planning Tool Manage Risks and Costs	Very high-level No installation detail Not a communication tool
Animation	Communicate ideas	Fast prototyping method Life-like graphics Intuitive to understand Can play with time control	No Physics & Not Real-Time No HIL/HITL No user interaction Not Detail-Oriented
Engineering	Feasibility analysis	Accurate Physics Models Domain Knowledge Develop Concept Procedure Detail-Oriented Regulated Requirements Trusted Standard Method	Abstract graphics Not real-time Time consuming No full scale HIL / HITL Not a communication tool
Training in Full Mission Simulator	Training operational excellence	Life-like graphics Real-time & Realistic physics HIL & HITL No familiarization required	Not versatile Often few closed-end scenarios Tedious to create new scenes
VPOO	Designing & Testing New procedures	fast prototyping method Versatile: open-end Scenarios Life-like graphics Realistic physics HIL & HITL No familiarization required Export to 4D animation	Only affordable for prestige or one-off operations Disconnected from planning tools Disconnected from field data

wind turbines (OWT) are installed in wind struck areas. To minimize weather-based downtime, the speed of installation, maintenance, and decommissioning operations is mission critical. Wind parks and OWT get larger and further away from shores (Lacal-Arántegui et al. 2018). Because transition pieces and windmills can weigh several thousand tonnes, installation and decommissioning are normally performed by jackup vessels or moored platforms equipped with powerful heavy-lifting cranes that lift monopiles. The industry faces many challenges when planning decommissioning: little experience with wind parks decommissioning and non-standard equipment design and installation (Topham and McMillan 2017). Installation is a major cost driver of wind power, and if campaign planning tools provide cost and risk monitoring, the installation methods are not mature and scalable and do not take advantage of VPOO (Asgarpour 2016).

Installing and decommissioning platforms weighing several thousand tonnes involves barges or Semi-Submersible Heavy Lifting Ships and Semi-Submersible Crane Vessels. Hooking-up platforms' topside to jackets in shallow waters requires high-precision in the position of the vessel and lifting. The more than 7000 offshore oil and gas production assets around the world are aging (Cheng et al. 2016), with over 475 in total in the UK seas (Jones et al. 2019), at least 153 decommissioning projects are planned over the next 10 years in the North Sea Basin (Vieira 2016). These projects involve safely plugging and abandoning subsea wells, disconnecting pipes from the productive machinery on the topside, and removing the topsides, jackets, and pipelines. Platform equipment and architectural layout are not standard, and safely speeding up operations requires careful planning. Marine growth, modified and degraded assets are elements complicating the operations.

Momentarily interrupting oil and gas production represent a million-dollar shortfall, per minute. Offshore platform equipment modification operations, or retrofits, often involve installing or replacing bulky equipment through narrow passages without stopping production. Because updating as-build drawings is generally neglected during commissioning and installation, MMO operation planning depends on point-cloud and/or photogrametry 3D scans of oil platforms for 3D model acquisition (Anderson and Barvik 2020; McGuire 2019). The scans are also necessary to perform 'clash detection' to verify that the new equipment fits in the target place. The 100% nonstandard commissioning and decommissioning operations are performed with mobile or platform cranes or ancillary winches, but whole platform modules of several hundred tonnes can also be installed as conventional rig.

Seismic survey vessels are rigged with expensive kilometres-long cables, which are complex and time-consuming to deploy in or recover from the sea. Because of the high variety of on-board equipment and vessel size, the industry is characterized by a low standardization of deployment and recovery procedures both for normal or emergency situations. Furthermore, the low-level of automation, the lack of visibility, and the sheer amount of control system information impair the situation awareness of the human operators(Sadjina et al. 2019). Seismic equipment accounts for a significant part of the ship's costs (M/S RAMFORM SOVEREIGN 2008) reports 34% of the $87m whole cost of a seismic vessel. The cost of damage or loss of equipment amounts to several hundred thousands of US dollars. Discovering the safest and fastest deployment and recovery, designing contingency procedures, and training communication to deck personnel is key to reduce incidents and down time.

Riser installations often involve multiple vessels performing the operation simultaneously (SIMOPS), with cranes and Remotely Operated Vehicles (ROVs) working in unison. The seakeeping and stability of the vessels, the hydrodynamic properties of the installed structures, and the capability of the tensioners are key. Oil fields are installed in always deeper waters, increasing the duration of the commissioning operation: the industry needs better equipment and smarter procedures. Activity Specific Operating

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Figure 3. Use of VPOO, Courtesy of Equinor, Aker Solutions, Kongsberg Marine, Subsea 7.

Guidelines (Chrolenko et al. 2018) are tables specific to a vessel's Dynamic Positioning (DP) System and activity to perform, taking the DP capability- or limitation; into account. The ship's optimal heading might be weather-specific, depending on orientation and strength of the waves, the current, and the wind. This has an impact on 'if-and-how' the operation is to be performed. As many failure in pipes can be traced to mishandling during installation (Dag Fergestad and Svein Are Løtveit 2017), simulation of operations is used in the industry to prepone possible errors in the control system and procedures earlier in the projects when the control systems are still onshore (McGuire 2019).

Fish farms are normally installed in sheltered areas with sometimes strong tidal currents, leading to short commissioning and operational (pumping life fish into the tanks) windows. This booming industry is still plagued by frequent work injuries and even fatalities (Holen et al. 2019; Holmen et al. 2017). With increasing fish farm cage sizes and locations moving to more open seas or offshore OFFSHORE FISH FARMING -- SalMar ASA (2018), it is important to identify risks and improve the procedures when mooring the fish cages, and loading the fish from the cages to the well boats, planning for contingency when a propeller get stuck in the mooring, or the well boat experiences a blackout or a dangerous imbalance in the tanks of the live fish carriers. As in other maritime industries, training simulators are developed to raise awareness towards the importance of environmental and humans factors in risk assessment (Holmen et al. 2017).

Figure 3 illustrates the use of VP in planning offshore operations. The image in the top left is taken from the aft bridge during a simulation of a fish farm operation. The top right shows a bird's eye view of a concept of a floating wind turbine installation (Courtesy of NTNU Ålesund, SFI Move). The middle right is an under-lower deck CCTV picture of a riser operation (Courtesy of Aker Solutions and Subsea 7). The middle left shows a concept study of a jacket installation using conventional barges. In the lower left is a picture of the instructor station of a seismic simulator (Courtesy of Kongsberg Marine). The lower right is a picture taken from the debrief room during the simulation a maintenance operation installing a balcony on the Sleipner Platform (Courtesy of Aker Solutions and Equinor). Table 2 describes the criteria used for the analysis of Table 3. Offshore operations are similar to moon landings, with the added component of SIMOPS or operations requiring an advanced level of cooperation between team members of different backgrounds, e.g. the Offshore

Table 2. Offshore Operation Criteria.

Criteria	Description
Heavy Lift	Lifts of more than 1000T, requiring dedicated crane equipment Requires Ballast, Mooring, and Anti-Healing Mechanisms
Specific Equipment	Custom-Made Rigging, Lifting, Tensioning, and Control Systems Subject to redesign during the project, requires rapid VP Not possible to reuse generic crane in simulator
Team Coordination	Different Roles Cooperating During Operation on the Same Vessel or Rig Requires different work stations during simulation
SIMOPS	Multiple Vessels Involvement, Translating to Multiple Bridges or Crane Stations in Simulator
Environmental Loads	Waves, Wind, and Currents Have a Major Impact on the Operation
DP/Control System	Dynamic Positioning, Anti-Heave or Tension Control, Ballast Control Systems Are Necessary Often real dedicated hardware is used during simulation
Collision	Operation Cannot Be Performed Without Contact Between Equipment Parts
Mooring & Ropes	Cable, Chains, or Fiber Ropes Are Involved in the Operation Vessel must be moored to perform operation
Hydrodynamics	Involves Vessels and Requires Accurate Response (strip or panel theory) Involves objects lifted down or up through water or under water

Table 3. Offshore operations characteristics.

Sector	Specific Equipment	Team Coordination	SIMOPS	Environmental Loads	DP/ Control System	Collision	Mooring and Ropes	Hydrodynamics
Wind Turbine Installation	++	+	-	++	++	++	++	+
Seismic Operation	++	+	+	++	+	++	++	++
Platform Installation & Decomm.	++	+	+	++	–	++	++	+
Riser and Subsea	++	++	++	++	++	++	++	++
Platform MMO	-	+	-	++	–	++	++	+
Aquaculture	+	+	-	++	++	+	++	++

Construction Officer, ROV pilots, the contractor project manager, the DP officer and captain, client representatives, the crane operator, etc. At first, we expected that operations from very different industries would have little in common, but a closer look at their operations' nature show a lot of overlap. The next section approaches the functional requirements of their VPOOs.

3. Functional requirements

This section addresses the requirements for simulation software and simulators to qualify as appropriate for VPOO.

3.1. Low familiarization requirement

High quality visuals and high fidelity 3D models with specific textures are important both for user engagement and for the information they convey: colour coding, marking, and 3D perspective. They satisfy the need for familiarization in the sense that the user does not need training to understand what the simulator shows. Immersive environments such as bridges and crane cabins with a surround dome for wrapped wall projection are preferred over VR and wall-mounted screens because they guarantee the required depth and provide the impression of perspective as pictured in the Figure 4, depicting as well CCTV displays, Survey Screen, and offshore-grade Winch and DP controls. 3D sound for winch, motor, wind, and collision is also a requirement to increase realism and immerse the engineers and operators in the situation. In the Standards of Training, Certification and Watchkeeping (STCW) DNVGL-ST0033 (DNV GL 2017), which gathers the requirements for simulator systems for training and assessment, equipment has to be as realistic as possible such that the trainees or students do not have to familiarize to different or novel types of interface and controls.

During the early iterations of VPOO, generic controls can be used, such as controlling a crane or a vessel with a gaming joystick. This is especially useful when prototyping on a laptop or desktop solution. But when planning for the detailed procedure, dedicated offshore hardware is needed to decrease the familiarization level. ROV pilots have to control simulated ROVs with the real chairs and handles, DP officers have to interact with real DP handles and software, and crane operators have to sit in industrial grade crane chair and control the crane via the same Human Machine Interface (HMI). The systems need to be fed with specific signals (NMEA, Modbus, etc.) coming from sensors, which have to be emulated based on the physical phenomena they measure: wind speed, water current speed, cell load on the top of a crane boom tip, positioning for GPS, CysCan, RadaScan, HIPAP, Motion Reference Unit (MRU), Gyro etc. This in turn has be simulated by a real-time physics engine. This eliminates the need for crew familiarization and puts the simulation in a real environment in the sense that the dedicated offshore control system should not differentiate between the synthetic world and the real one. This approach necessitates a higher model refinement such as emulating

Figure 4. Full Mission Bridge Simulator, courtesy of Offshore Simulator Centre.

sensors or thruster signals (often NMEA over UDP) to allow for the integration.

3.2. Realistic physics

To support Hardware in the loop (HIL) and Human in the the Loop (HITL), the simulation must support real-time time-domain physics, with collision detection, aerodynamics, and hydrodynamics of ships, thrusters, and wetted objects (Lee and Roh 2018). As Table 5 shows, few software packages can cover all the physics domains. Integration and co-simulations thus have to be performed. The whole simulated environment needs to be represented in the physics simulation. The position and orientation of the objects, force and moment, and thrust can be measured by virtual sensors and fed to crane displays, navigational screens, or nautical map system ECDIS, and control applications (DP system, Anti-Heave, or Anti-ballast).

3.3. Flexibility and rapidity

Flexibility addresses the possibility to build and run various and rich scenarios, with complex environmental conditions such as wind, wave, and current. It also addresses the possibility to reuse models from a library of vessels and rigs, lifting equipment, load objects, ropes, chains, wires, subsea equipment, ROVs, control systems, and their failures modes. Reusing models is key to rapid prototyping (Skjong et al. 2018). Nonetheless, new operations often involve nonstandard equipment and it is essential to acquire and model them in a rapid way, such that the operational planning and the higher level systems engineering do not slow down. Engineering 3D models, such as ISO-10303-21 STEP files, often have a lot more details (meshes) than required for visualizing and too many polygons for smooth visualization in 3D graphics environments. Generating low-poly high fidelity 3D models are necessary to capture the exact collision model, and, more importantly, the exact buoyancy, weight, and weight distribution. The process of simplification and import of 3D models, keeping their structure but giving them a visual appeal and realism through textures, needs to be performed efficiently. This process is sometimes performed manually, but it is time-consuming: optimizing a vessel model takes around 300 hours. Some tessellation tools for importing CAD models into game engines are on the market (Pixyz 2019), and some others can even keep the structure in the model and create a physic model with a physics engine (Algoryx Momentum 2019).

In summary, VPOO Simulators have to offer experts a low familiarization threshold and provide a spatial partition reflecting the organizational structure of the operations they are engineering, providing the possibility of HIL and HITL. VPOO simulation software have first to be flexible, able to reuse models, and second to be rapid to import with 3D CAD models that model the simulation. The physics engines provide real-time simulation in time domain, with wire, collision, hydrodynamics, and multi-body physics. Now that we have detailed the demanding requirements set by VPOO with respect to software, hardware, and simulation model, we can investigate the regulative requirements.

4. DNV regulation

Compliance with DNV GL offshore standards is very often a contract requirement for marine operations, and they are a representative benchmark for international offshore regulation. This section briefly probes mentioned open-access regulation for the use of virtual prototyping of offshore operations. The regulation focuses on Safe Job Analysis (SJA), which includes Hazard Identification (HAZID), Hazard and Operability (HAZOP) Study, and procedure HAZOP. As mentioned in the standard, ‘The HAZOP shall refrain from finding solutions and carrying out redesign’ (DNV GL 2017a). Procedure

Table 4. Keyword Search in DNV Standards.

Document	Title	Procedure	Planning	Analysis	Simulation	Prototype
DNV-OS-H101 (DNV 2011)	Marine Operations, General	17	12	23	0	0
DNVGL-RP-N101 (DNV GL 2017a)	Risk Management in Marine and Subsea Operations	92	18	25	0	0
DNVGL-RP-N102 (DNV GL 2017a)	Marine operations during removal of offshore installations	24	33	25	0	0
DNVGL-RP-N103 (DNV 2011a)	Modelling and analysis of marine operations	12	14	96	33	0
DNV-OS-H102 (DNV GL 2017b)	Marine Operations, Design, and Fabrication	15	84	31	0	0
DNV-OS-H201 (DNV 2012a)	Load Transfer Operations	255	26	15	0	0
DNV-OS-H202 (DNV 2015)	Sea transport operations	49	16	14	1	0
DNV-OS-H203 (DNV 2012b)	Transit and Positioning of Offshore Units	31	34	0	0	0
DNV-OS-H204 (DNV 2013a)	Offshore Installation Operations	17	12	0	0	0
DNV-OS-H205 (DNV 2014)	Lifting Operations	82	22	13	0	0
DNV-OS-H206 (DNV 2014)	Loadout, transport, and installation of subsea objects	34	29	2	0	0
DNV-RP-H103 (DNV 2011a)	Modeling and Analysis of Marine Operations	12	19	123	33	0
DNVGL-ST-0033 (Maritime simulator systems 2019)	Maritime simulator systems	13	15	6	81	0
DNV-RP-A203 (DNV 2013b)	Technology Qualification	30	5	92	5	23

HAZOP shall be performed by interdisciplinary teams. It likewise adds,

> The timing for a system HAZOP is typically in an advanced stage of engineering, before the design is fully finalized and the system built. It is important that the implementation of the results from the HAZOP in the design is possible without high consequential costs or rework.

This reflects the conventional use of VP at a mature stage of the design as mentioned in the introduction, but has to be contrasted with the high cost of identifying an unworkable operation late in the design phase.

The common way engineering operations proceed is based on simulated ship response and weather and sea state statistics to calculate the operability of an operation, by using time-domain engineering tools such as SIMA or Orcaflex to get statistics about the success of the simulated operations often with mock-ups of control systems and emulated human interaction. The result of the simulation will be a maximum wave height for the operation, which will divided by a safety factor accounting for the uncertainty in the weather prediction.

Table 4 counts the occurrences of relevant keywords in the DNV standards, and use of the figures are proxy for the importance of the concept in the standard. Fourteen selected standard documents are related to maritime and offshore operations, and one addresses offshore technology qualification.

All the investigated DNV standard documents mention the terms 'procedure' and 'planning'. Four out of 14 mention 'simulation'. This shows the lack on emphasis on VP for planning operations. (DNV 2011a) mentions the terms 'analysis' 133 and 'simulation' 33 times, but the focus is not on testing the whole operation in detail, but rather on identifying the 'starting and interruption criteria' depending on a reliable weather forecast. VPOO puts together the moving parts of the future operation and simulates them in a lifelike situation. One of the main additions made by updating the DNV Standard for Maritime Simulator Systems from DNV (2011b) to Maritime simulator systems (2019) is that the new standard proposes the use of simulators for 'science, and the planning of maritime operations'. Interestingly, (DNV 2013b) is the only document to refer to 'prototypes', and the word 'procedure' is used both in the context of the modus operandi of the new technology and the the way of testing and qualifying the technology in question. In other words, it does not place the technology in the broader context of the advanced maritime or offshore operation.

DNV regulation does not put forward a dedicated methodology for VPOO. But there are acknowledgements that mission planning can be performed using simulators. The next section investigates the software and simulator landscape.

5. Virtual prototyping software and simulators

This section illustrates an intensive effort of mapping the software and simulators complying with the requirements set in the previous sections.

5.1. Simulation software

We focus on simulation software widely used -- or commonly used in the offshore and maritime industry. Known as domain-specific simulation software, these are specialized software and they have only begun to be compatible with other tools recently thanks to co-simulation protocols such as FMI (Association Project M 2014). These simulation types have been excluded: logistics, event-based, economics, Monte-Carlo, concept illustration, and animation software (no physics) such as (Concept illustration and animation 2020).

Table 5 gives an overview of the software packages with their respective domain of application. As seen in

Table 5. Simulation software characteristics (T:Time, RT: Real-Time, F:Frequency).

Software	Results domain	In-the-Loop	FEM	Rigid body physics	Wire physics	Control plugins	Hydrodynamics	CFD	Multisystem	Graphics -- Visuals
20-Sim(20-sim software features 2020)	T, F	HIL		✓		✓			✓	Advanced
ABAQUS (Abaqus cae 2020)	T, F	None	✓	✓	✓		✓	✓	✓	Advanced
Adams (Adams 2020)	RT, T, F	HIL		✓	✓	✓		✓	✓	Advanced
AGX Dynamics (Algoryx 2020)	RT, T	None		✓	✓	✓	✓[1]		✓	Advanced[2]
AMESim (Amesim 2020)	RT, T, F	HIL, HITL				✓	✓		✓	Advanced
ANSYS CFX (Ansys cfx 2020)	T, F	None	✓				✓	✓		Advanced
CATIA (Catia 2020)	None	None								Advanced
COMSOL (Comsol multiphysics 2020)	T, F	None	✓	✓			✓	✓		Advanced
Dolphin (DOLPHIN simulation software 2020)	RT, F	HIL, HITL		✓	✓	✓	✓		✓	Life-Like
Dymola (Dymola 2020)	RT, T, F	HIL				✓			✓	Advanced
Fathom (OSC)[3] (Osc 2020)	RT, T, F	HIL, HITL		✓	✓	✓	✓		✓	Life-Like
Fhsim (Fhsim 2020)	T, F	None			✓	✓	✓			Basic
HyperWorks Suite (Hyperworks suite 2020)	T, F	None	✓				✓	✓	✓	Advanced
KSim[4] (Ksim 2020)	RT, F	HIL, HITL		✓	✓	✓	✓		✓	Life-Like
MapleSim (Maplesim 2020)	RT, T, F	HIL		✓		✓			✓	Advanced
MatLab Simulink (Matlab simulink 2020)	RT, T, F	HIL				✓	✓[5]		✓	Basic
OpenFOAM (Openfoam 2020)	T	None	✓				✓	✓		Advanced
OpenModelica (Openmodelica 2020)	T, F	HIL				✓			✓	Basic
NI Labview (Ni labview 2020)	RT, T, F	HIL				✓			✓	Basic
Orcaflex (Orcaflex 2020)	T	None		✓	✓	✓	✓		✓	Advanced
RecurDyn (Recurdyn 2020)	T	None		✓	✓					Advanced
Rhino 6 (Rhino 6 2020)	T	None	✓	✓			✓	✓		Advanced
RTMaps (Rtmaps 2020)	RT	HIL, HITL				✓			✓	Advanced
Scilab (Scilab 2020)	RT, T, F	HIL, HITL	✓			✓		✓	✓	Advanced
ShipX/Vessim (Shipx 2020)	T, F	None					✓			Basic
SIMA (Sima 2020)	T	None		✓	✓	✓	✓		✓	Advanced
SimScale (Simscale 2020)	T	None	✓	✓			✓	✓		Advanced
SolidWorks (Solidworks 2020)	T, F	None								Advanced
Star CMM+ (Star cmm 2020)	T	None	✓				✓	✓		Advanced
Vortex Studio (Vortex studio 2020)	RT, T, F	HIL, HITL		✓	✓	✓	✓		✓	Life-Like
WAMIT (Wamit 2020)	F	None			✓	✓	✓			Basic
Xflow (Xflow 2020)	T	None	✓				✓	✓		Advanced

[1]basic, neither strip nor panel theory
[2]with Unity Plugin
[3]integrator
[4]integrator
[5]with (Fossen and Perez 2004)

Table 6. Simulator solutions.

Simulator	HIL	HTIL	VR	Crane	ROV	Ship	Engine	AB	Fast VP
midrule Aboa Mare (Aboa mare 2020)	✓	✓				✓	✓		
K-Sim (Ksim 2020)	✓	✓		✓	✓	✓	✓		✓
SIMSEAS (Simsea 2020)	✓	✓		✓	✓	✓	✓		
OSC Simulator (Osc 2020)	✓	✓		✓	✓	✓	✓	✓	✓
Transas simulator (Transas 2020)	✓	✓		✓	✓	✓	✓		
FREMM Simulator DGA-Naval Group (Fremm simulator dga-naval group 2020)	✓	✓	✓	✓		✓	✓		
Simuladore Full Mission (Usp 2020)	✓	✓		✓		✓			
STR Korea (Str korea 2020)	✓	✓		✓		✓			
iPort Aker Visioneering(Iport aker visioneering 2020)	✓	✓	✓	✓	✓	✓		✓	✓
Marin (Marin simulator 2020)	✓	✓	✓	✓	✓	✓		✓	✓
VSTEP(Vstep nautis 2020)	✓	✓	✓	✓	✓	✓		✓	
RheinMetall (Rhein metall 2020)	✓	✓	✓	✓	✓	✓		✓	
Tree C (Tree 2020)	✓	✓	✓	✓	✓	✓		✓	✓

Section 3, to make a realistic simulation, one has to combine specific domain such as hydrodynamics and rigid body physics, but no single tool can cover these needs; it has to be a co-simulation.

Finite Element Modeling (FEM) engines do not perform in real-time, which makes it impossible to compute deformation due to crash or rope elongation in a timely manner. Even though online (real-time) Computational Fluid Dynamic (CFD) is an active subject of research (Hosain and Fdhila 2015), no commercial software can provide CFD in real time either and simulation software have to resort to strip or panel theories to run simulations with humans. Few software packages comply with the requirement of HIL, HITL, real-time simulation in time domain, with wire, collision, hydrodynamics, or multi-body physics, which are necessary for VPOO. The exceptions are Dolphin, Vortex, KSim, SIMA and Fathom[1] .

5.2. Maritime simulators

While DNV provides a list of around 180 certified simulators (DNV 2020), Table 6 shows an non-extensive overview of the full mission simulators, based with our best knowledge. Simulator centres specialize in training on equipment (Fremm simulator dga-naval group 2020), or maritime traffic and nautical skills (Aboa mare 2020; Transas 2020; Rhein metall 2020; Usp 2020), or defence (Fremm simulator dga-naval group 2020; Rhein metall 2020). A few solutions providers can offer VPOO systems: Tree C (Tree 2020), K-Sim(Ksim 2020), Aker (Iport aker visioneering 2020), Marin (Marin simulator 2020), and OSC (Osc 2020). The next section will investigate the literature for such methodology.

6. Literature review

6.1. Methodology

Searches were conducted in 'Google Scholar', 'Science Direct', 'One Petro', and 'Scopus' with the following keywords:

- 'full mission', 'offshore'
- 'full mission bridge simulation', 'operational procedures'
- 'offshore operation simulation'
- 'mission planning', 'virtual prototyping'
- 'virtual prototyping of offshore operations'
- 'virtual prototyping of maritime operations'
- 'offshore simulator', 'simulator AND seismic AND vessel', 'simulator aquaculture'

Search results were then filtered by ignoring publications with 'Markov', 'Bayesian', 'Petri nets', 'medical operations', 'navigation training', 'drilling', 'equipment training', 'operational training', and 'systems engineering'. Only publications related with time domain simulation, HIL, HITL, and offshore operations were considered. References from the results were checked and added if the publication corresponded to the set criteria. The taxonomy of the review is illustrated in Figure 5. Simulators must offer the possibility to test procedures with a general physics engine, in real time. VPOO can be first performed on a desktop solution before being implemented in a simulator facility; this is reflected in the taxonomy.

6.2. Results

Table 8 shows the result of an intensive search of publications on VPOO. Systematic registering of keywords is absent of this part of engineering publication, which hinders methodological research. The terminology of Virtual Prototyping of Offshore Operation is not anchored; for example some papers use the vague term of 'virtual reality'. The results are few.

The findings of Wang et al. (2019), Wang et al. (2010) show the relevance of Figure 2, in which feedback to procedures, simulation model, hardware layout, and procedure are identified. Zhang et al. (2017) and Yu et al. (2017) extensively cover the

[1]Algoryx Dynamics (Algoryx 2020), which is a physics engines used by KSim, Tree C, SMSC, and OSC.

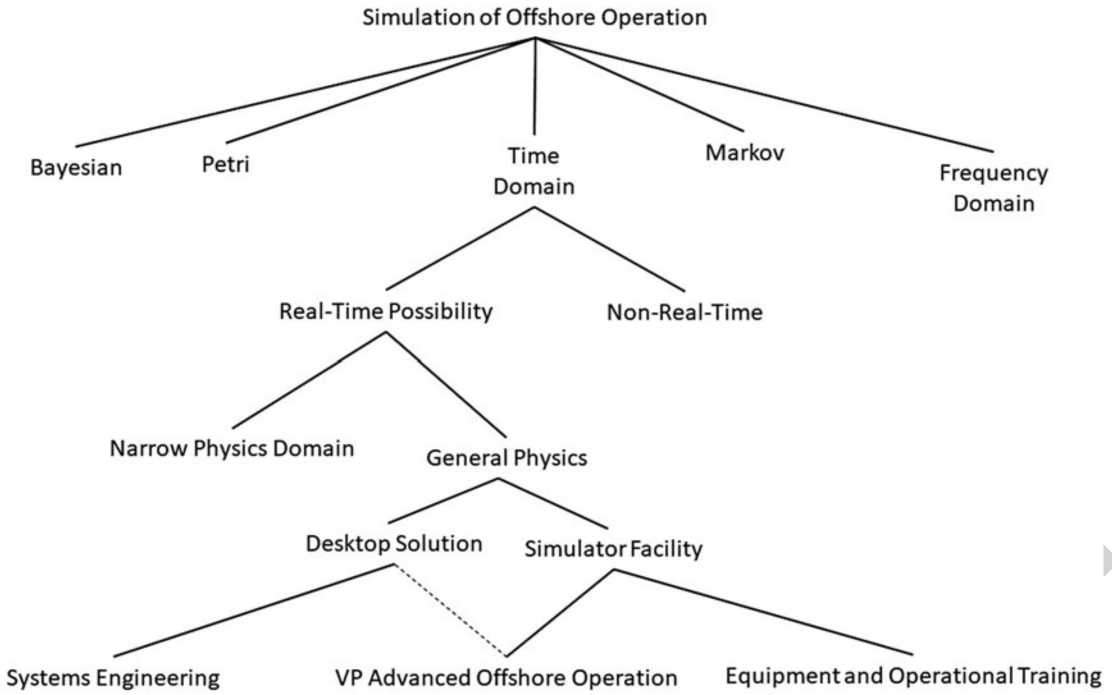

Figure 5. Taxonomy of Simulators for VPOO.

Table 7. Literature review, keywords.

Document	Title	Author keywords
Wang et al. (2019)	Virtual Reality Simulations for Dynamic Positioning Floatover Installation	Virtual Reality; Virtual Simulation; Dynamic Positioning; Floatover Installation
Wang et al. (2010)	Virtual Simulations of VLCC Class FPSO-SYMS Mating Operation	FPSO; SYMS; virtual simulations; Mating operation
Zhang et al. (2017)	A mathematical model of virtual simulation for deepwater installation of subsea production facilities	virtual reality, installation simulation, mathematical model, high reality
Yu et al. (2017)	A virtual reality simulation for coordination and interaction based on dynamics calculation	Virtual reality; collaborative operation; HCI; dynamics calculation; offshore lifting and installation
Chrolenko et al. (2018)	Fully Coupled Time Domain Simulation Model Used for Planning and Offshore Decision Support During Riser Replacement Operations	No keyword
Tannuri and Martins (2018)	Application of a manoeuvring simulation center and pilots expertise to the design of new ports and terminals and infrastructure optimization in Brazil	No keyword
Voogt et al. (2014)	Integrating hydrodynamic and nautical studies for offshore LNG operations	No keyword
Armaoğlu and Monti (2014)	Advantages of using a time-domain approach for dynamic positioning pipelay studies	No keyword
Time and Torpe (2016)	Subsea compression -- Åsgard subsea commissioning, start-up and operational experiences	No keyword

mathematical validation and computer architectural part of VPOO, but without mentioning the human factors and the engineering benefits of the simulator for VPOO. The systems architecture is presented with blurred lines between the planning process itself, the simulation software, and the hardware architecture. Even though it describes a port engineering methodology, (Tannuri and Martins 2018) has been included in the review because of the proximity between offshore and port activities, the use of a full mission simulator, the cooperation between engineers and mariners, the common necessity to have realistic ship models, and the stress of human factors. With a particular procedure in the background of the study, (Voogt et al. 2014) advocates for closer cooperation between engineering and mariner teams, integration of better hydrodynamics model and their improvement through real-life data. Armaoğlu and Monti (2014) presents a methodology to choose the scenarios to simulate the operation, anchoring the necessity to train the dynamic positioning officer for various hazardous cases. Time and Torpe (2016) presents the commissioning, start-up, and operational aspects of the Statoil Åsgard project, which was a first of its kind subsea installation, and brings valuable insight from the parent project into the commissioning part, with details on how the engineering team planned the operation. It is not mentioned in the paper, but the training took place in the Offshore Simulator Centre. Noticeable time savings were reached by totally rewriting the procedures during the VP sessions and intensive team training. The paper also describes how an

Table 8. Literature review.

Document	Summary	Engine	Findings of the VP sessions
Wang et al. (2019)	Platform commissioning Heavy Lift	STC B.V	Familiarization to simulation is key HMI layout not optimal Need better contingency plans Simulated winches are not realistic Identified skills gap
Wang et al. (2010)	FPSO towing, SIMOPS, mooring	STC B.V	Mooring configuration redesign required Need better sensor during operation HMI not optimal Evaluate the feasibility of normal and contingency operation Human factor/communication and critical phase awareness Methodology is complementary to numerical simulation, model test and field tests No procedure methodology
Zhang et al. (2017)	Deep water Crane Operation Model validation	Vortex	Brief validation of the model with Orcaflex and SESAM
Yu et al. (2017)	HW/SW Architecture and modeling of operation Collaborative Simulation	Vortex	Brief validation of the model
Chrolenko et al. (2018)	Riser Operation ASOG, HIL (DP), contingency	SIMA, SIMO, RIFLEX	SIMOPRO Riser replacement methodology Optimized operation Contingency planning in case of wire break or power black out Ånensen and Gundersen (2017) Onboard Decision Support System (ODSS)
Tannuri and Martins (2018)	Full Mission, Multipurpose Virtual Prototyping, Port Design	Purpose Built	Berthing Analysis Infrequent operations Human factor Importance of 3D model of seabed and coast VP engineering of ports with engineers, captains, and pilots
Voogt et al. (2014)	Tandem vs side-by-side FLNG Berthing	MARIN	Advocates for physical closeness between engineering teams and full mission simulator Need for collaboration between engineering and operational teams Models need to be validated by online/offshore data, but it is missing
Armaoğlu and Monti (2014)	DPO training for pipe playing	MARIN	Preventing buckling and overstress on the pipe Optimize operation against downtime Plan contingency
Time and Torpe (2016)	Subsea Operation of Åsgard	OSC / Fathom	Trained a crew of DP, ROV, Crane Operator Rewrote procedure: shortened commissioning period Monitoring via satellite link Team awareness, common understanding Discovered the hardware and software issue during onshore testing Knowledge transfer from one campaign to the other

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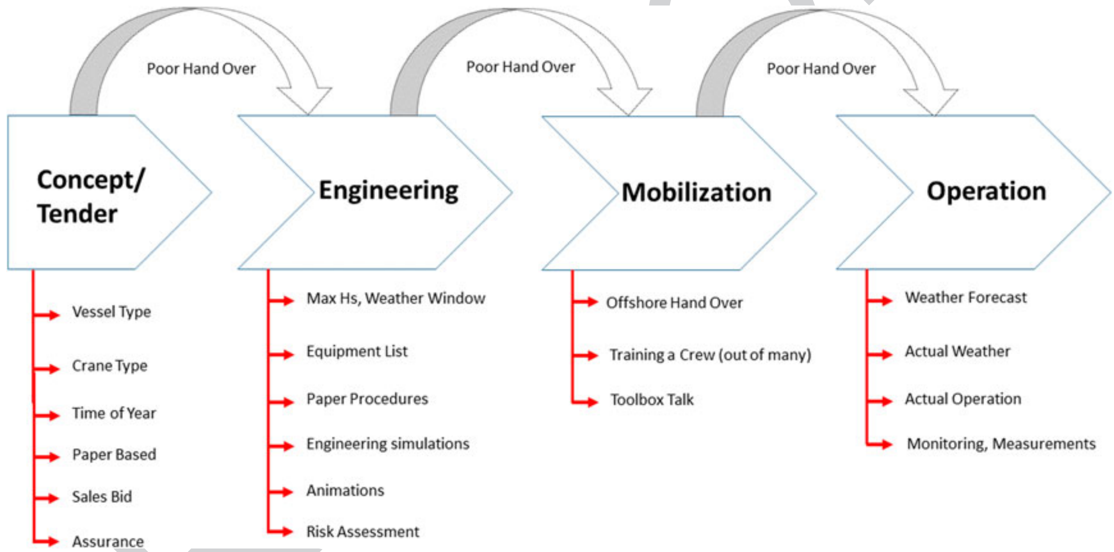

Figure 6. Without integration between the project phases.

offshore campaign was followed from the onshore remote control center.

The literature search did not provide research that addresses VPOO for wind, maintenance, aquaculture, and seismic. While a significant number of papers on VP of windmills have been found, none of them match the VPOO criteria. Regarding aquaculture, Holmen et al. (2017) describes a simulator and a training curriculum for fish farm operations, but not a VPOO simulator. The scarce academic literature on VPOO for MMO, seismic, and aquaculture is less surprising: while offshore aquaculture is still booming and has not reached the maturing phase, seismic and maintenance rely on private and legacy solutions.

The following section will discuss possible future directions.

7. Future of virtual prototyping

Offshore operation planning spans many years before the real operation takes place. They are generally segmented in different maturation phases, each with its own deliverables, but with limited flow of information because they are paper-based and driven by different departments, as illustrated in Figure 6. There is no common engineering tool gluing the phases together; simulations and animations have to be done from scratch at the beginning of each phase. We can identify

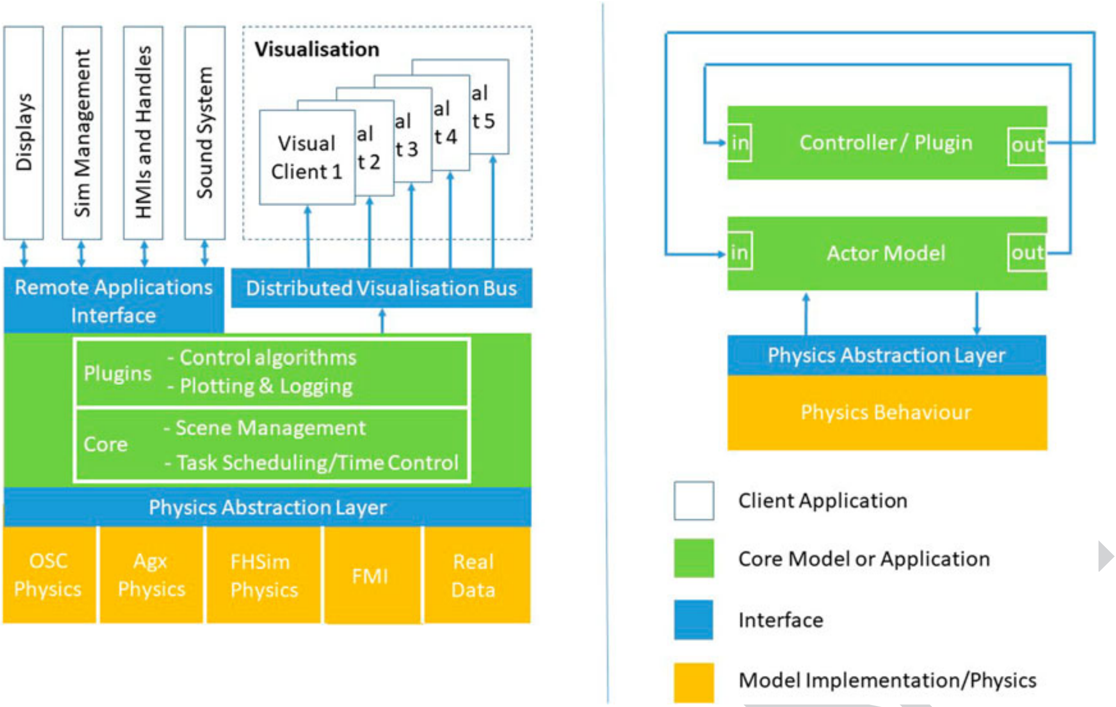

Figure 7. OSC Fathom Software Architecture, adapted from (Major et al. 2019).

a need for integration from tender to toolbox-talk and back to engineering; marine engineering contractors could use one single tool to test ideas, new concepts, integrate engineering calculations, communicate procedures and course of action, train and drill the relevant crew before the operation, monitor data for later analysis and for short term predictions, perform debriefs, and return on experience for later campaigns. On-board decision support ODSS, based on sensors and simulation, could augment the operators' reality with simulation predicting the behaviour of the system in 5 seconds, 30 seconds, 5 minutes, much like a parking assistant. Figures 1 and 6 show a picture with little or no direct feedback from operations. A lot of field data could be gathered during the real operations and used to improve the simulation models used in the conceptual, engineering, and training phases. ODSS have already been installed on offshore vessels (Chrolenko et al. 2018; Taby et al. 2011) and are good candidate for such systematic data collection.

Research should go further in the integration between the project phases. Figure 8 sketches a methodology supported by a tool that could span the whole lifespan of the offshore operation. VP should not start from halfway through the engineering project, when conceptual errors are expensive to mitigate, but earlier in the project. Gathering field data during the offshore operation, such as vessel response, vessel loading condition, crane loads, and environment will allow for the building of a response-based model and enfranchise offshore contractors from conservative safety factors. In the concept or sales phase, contractors will work on generic or library assets such as vessels, cranes, and modules used and tuned during previous campaigns.

Figure 7 shows how the model refinement can be achieved. Thanks to the physical layer abstraction, the simulation control (core) is agnostic about the actor's or asset's behaviour. This means that the latter can be refined during the life cycle of the project without changing the simulation itself, keeping the same tool. The engineer can work with a pure mock-up or a generic library asset of a vessel, crane, or subsea module during the concept phase, then improve it along the way until real data can be gathered to improve the model for a later campaign or operation. This is a hybrid approach, because the behaviour of the assets is originally model-based, but when data is acquired from operations it can get data-driven.

Similar to recordable replays in E-sports games, it is possible to record a simulation, not only in terms of audio and video, but in a more comprehensive manner. By recording the positions and orientations of all the objects in the simulation scene, together with all their static and dynamic properties (user commands, forces, tension, mass, sea state, weather etc.) at any time step, one can replay a simulation in a 4D way. Feeding back the recorded data to the visuals will create a 4D visualization tool one can interact with by playing with the time control, such as *backwards*, *pause*, *slow motion*, *fast forward*, or 3D viewer control, such as moving the camera freely from any perspective or any field of view. This is a radically new concept for VPOO, but not for gaming, as this feature is already used to replay a goal during a

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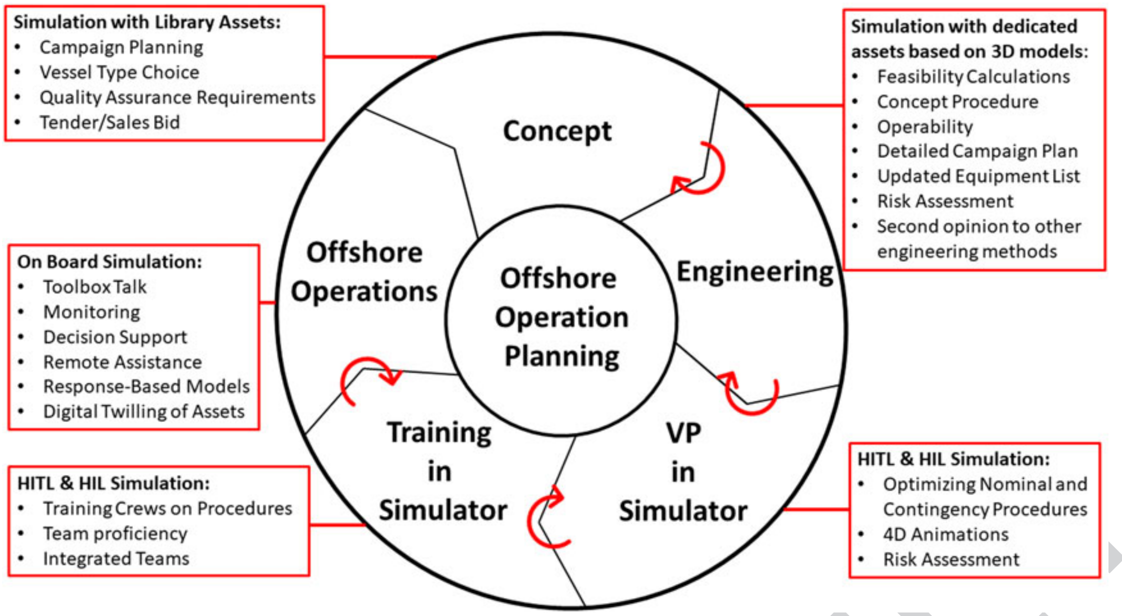

Figure 8. Planning offshore operations with integrated virtual prototyping planning tool.

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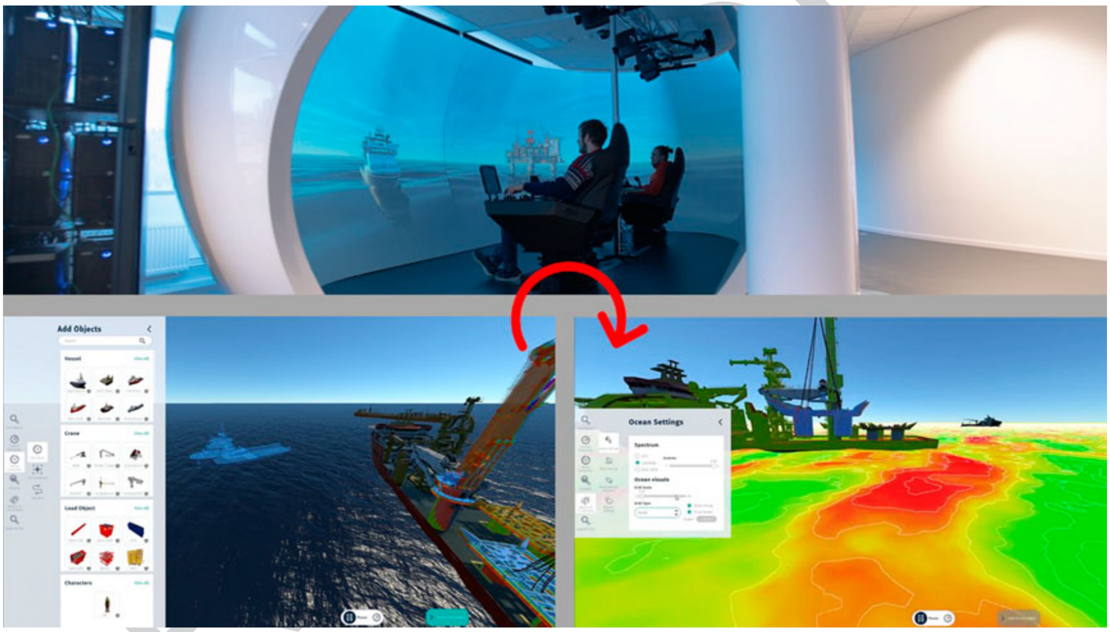

Figure 9. Planning Operations in Simulator, Courtesy of OSC and NTNU Ålesund Stretch Dome.

football match in a video game. This has both the advantage of providing the team members a common understanding of the operation by showing the operations from the perspective of one of their teammates, and of providing a more cost efficient alternative to reiterating the operation in the simulator. This new medium could be used as a new standard tool for SJA. Figure 9 depicts the life cycle of a project using the same simulation tool. On the lower left hand side, the engineers can build a scene from library assets and test their solutions on their desktops. Then the procedures can be tested and optimized, and crews can get trained (upper part of the figure). Finally the tool can be brought offshore and integrated with sensors such as radar-based wave scanners to train for the real lift a short term in advance. Onboard sensors measuring the systems state such as MRU, GPS, power consumption, crane position and work load, etc., combined with environmental data (wind, wave, current, sun light, neighbouring objects or coast). Human factor data such as communication, wearable sensors (hear beat, stress, eye sensor) can be logged and displayed in a historian view or real-time onboard in the operations control center and slightly delayed in a remote mission control center onshore via satellite link as in Time and Torpe (2016). This digital twin approach allows the planned procedures to be compared with the real operations, providing an enhanced feedback loop for the next planning campaigns.

8. Conclusion

This review provides the state of the art about the current methods and practices to plan advanced offshore operations. We first briefly present the planning process and relevant use cases, identify the functional requirements of VPOO, and analyse relevant solution providers, offshore regulation, and academic literature. We found that systematic search is laborious due to the lack of consistency in the wording in academic research. Although VPOO has numerous advantages, it is almost absent from the offshore planning methodologies in both regulative and academic contexts. A few actors are experimenting on the commercial side to deliver realistic simulation experience. VPOO contributes to identifying unworkable procedure or operations, to smoothing the handover from engineering to marine teams, and to increasing the team performance. This is because VPOO provides a comprehensive risk management analysis of operations and complements incumbent engineering software and current regulations on offshore operations by adding the human factor dimension. We advocate for an early use of VPOO in planning processes to identify the technical and human factors related a given installation method's show-stoppers. A discussion of future developments sketches the idea of a tool bridging the various project phases from tender and concept to actual offshore operation, and back to the concept of the next operation. VPOO should be the new standard for SJA and operation planning.

The same methodology can be used for planning unmanned offshore operations, as they must be prototyped and tested virtually and physically to an equal extent before they can be applied in productive operations. Removing the human from the operations decreases the cost of the real-life system because it significantly lowers the requirements for human safety. Nevertheless the transition from manned to unmanned will involve require training for more contingency and 'what if' scenarios. Hybrid and autonomous operations have to be tested in a more intensive way, because humans are creative and innovative and autonomous systems are not. This increases the relevance of VPOO simulators and the necessity of training semi-autonomous operations or autonomous systems interaction with external humans.

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Disclosure statement

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References Q5

Abaqus cae.(last accessed 2020 Jan 05). https://www.3ds.com/products-services/simulia/products/abaqus/abaquscae/.

Aboa mare. (last accessed 2020 Jan 05). https://www.aboamare.fi.

Adams. (last accessed 2020 Jan 05). https://www.mscsoftware.com/product/adams.

Algoryx Momentum. (accessed 2019 Nov 28). https://www.algoryx.se/products/algoryx-momentum/.

Algoryx. (last accessed 2020 Jan 05). https://www.algoryx.se/products/agx-dynamics.

Amesim. (last accessed 2020 Jan 05). https://www.plm.automation.siemens.com/global/en/products/simcenter/simcenter-cae-simulation.html.

Anderson S, Barvik S. IPTC-20087-Abstract Advanced Offshore Digital Inspection Methods; 2020.

Ånensen A, Gundersen G. Dynamic Positioning Conference DP Verification Study; 2017. https://dynamic-positioning.com/proceedings/dp2017/Operations--Ånensen--presentation.pdf.

Ansys cfx. (last accessed 2020 Jan 05). https://www.ansys.com/products/fluids/ansys-cfx.

Armaoğlu E, Monti P. Saipem SpA Advantages of using a time-domain approach for dynamic positioning (DP) pipelay studies; 2014. https://asmedigitalcollection.asme.org/OMAE/proceedings-pdf/OMAE2014/45370/V01AT01A003/2526078/v01at01a003-omae2014-23040.pdf.

Asgarpour M. Assembly, transportation, installation and commissioning of offshore wind farms. In: Offshore wind farms: Technologies, design and operation; 2016.

Association Project M. Functional Mock-up Interface for Model Exchange and Co-Simulation; 2014. https://www.fmi-standard.org/downloads.

An annual review of trends and developments in shipping losses and safety. Allianz Global Corporate & Specialty 8,862; 2019. https://www.agcs.allianz.com/content/dam/onemarketing/agcs/agcs/reports/AGCS-Safety-Shipping-Review-2019.pdf.

Baker CC, McCafferty DB. Accident database review of human-element concerns: What do the results mean for classification? In: International Conference -- Human Factors in Ship Design, Safety and Operation; Vol. 2000. RINA, Royal Institution of Naval Architects; 2005. p. 65–71.

Catia. (last accessed 2020 Jan 05). https://www.3ds.com/products-services/catia/.

Cheng JCP, Tan Y, Liu X. Application of 4D BIM for Evaluating Different Options of Offshore Oil and Gas Platform Decommissioning. https://pdfs.semanticscholar.org/45e2/10293f0589a1df5025f74ace58370e96a20e.pdf.

Chrolenko M, Gundersen G, Eikanger TE, Tveraaen T. Fully Coupled Time Domain Simulation Model Used for Planning and Offshore Decision Support During Riser Replacement Operations; 2018.

Comsol multiphysics. (last accessed 2020 Jan 05). https://www.comsol.com/release/5.4.

Concept illustration and animation as. (last accessed 2020 Jan 05). http://www.ciaas.no.

Dag Fergestad SO, S Svein Are Løtveit editors. Handbook on Design and operation of flexible pipes. NTNU, 4Subsea, SINTEF; 2017. https://www.sintef.no/en/ocean/handbook-on-design-and-operation-of-flexible-pipes/.

DNV GL. Recommended practice risk management in marine and subsea operations; 2017. http://rules.dnvgl.com/docs/pdf/dnvgl/RP/2017-06/DNVGL-RP-N101.pdf.

Dnv type certificate simulators. (last accessed 2020 Jan 05). "https://www.dnvgl.se".

DNV. Offshore standard lifting operations (VMO Standard-Part 2-5); 2014. https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2014-04/OS-H205.pdf.

DNV. Recommended practice modelling and analysis of marine operations; 2011. https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2011-04/RP-H103.pdf.

DNV. Offshore standard transit and positioning of offshore units; 2012. http://www.dnv.com.

DNV. Offshore standard offshore installation operations (VMO Standard Part 2-4); 2013. https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2013-11/OS-H204.pdf.

DNV. Loadout, transport and installation of subsea objects (VMO Standard-Part 2-6); 2014. www.dnvgl.com..

DNV. Recommended practice technology qualification; 2013. http://www.dnv.com.

DNV. Maritime simulator systems; 2011. https://rules.dnvgl.com/docs/pdf/DNV/stdcert/2011-01/Standard2-14.pdf.

DOLPHIN simulation software. https://www.marin.nl/storage/uploads/3613/files/DOLPHIN.pdf.

Dymola. (last accessed 2020 Jan 05). https://www.3ds.com/products-services/catia/products/dymola/.

DNVGL-ST-0033 Maritime simulator systems. DNV GL; 2017.

EMSA. Annual overview of marine casualties and incidents 2017. 2014:139.

Fhsim. (last accessed 2020 Jan 05). https://fhsim.no/.

Fossen TI, Perez T. MSS Toolbox ; 2004. https://github.com/cybergalactic/MSS.

Fremm simulator dga-naval group. (last accessed 2020 Jan 05). https://www.naval-group.com/en/news/naval-group-delivers-new-visual-defence-simulators-intended-for-the-french-navy-in-brest-and-toulon/.

Gordon RP, Flin RH, Mearns K, Fleming MT. Assessing the human factors causes of accidents in the offshore oil industry. In: SPE Health, Safety and Environment in Oil and Gas Exploration and Production Conference; 4. Society of Petroleum Engineers; 1996. http://www.onepetro.org/doi/10.2118/35970-MS.

Håvold JI, Nistad S, Skiri A, Ødegårdac A. 2015. The human factor and simulator training for offshore anchor handling operators. Saf Sci. 75:136–145.

Holen SM, Yang X, Utne IB, Haugen S. 2019. Major accidents in Norwegian fish farming. Saf Sci. 120:32–43.

Holmen IM, Thorvaldsen T, Aarsaether KG. Development of a simulator training platform for fish farm operations. In: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering -- OMAE; Vol. 3B-2017. American Society of Mechanical Engineers (ASME); 2017.

Hosain ML, Fdhila RB. Literature review of accelerated cfd simulation methods towards online application. In: Energy Procedia; Vol. 75. Elsevier Ltd; 2015. p. 3307–3314.

Hyperworks suite. (last accessed 2020 Jan 05). https://altairhyperworks.com/.

Iport aker visioneering. (last accessed 2020 Jan 05). https://www.akersolutions.com/what-we-do/products-and-services/modifications/.

Jones D, Gates AR, Huvenne VASEP. 2019. Autonomous marine environmental monitoring: application in decommissioned oil fields. Sci. Total Environ.. 668:835–853.

Ksim. (last accessed 2020 Jan 05). https://www.kongsberg.com/digital/products/maritime-simulation/.

Lacal-Arántegui R, Yusta JM, Domínguez-Navarro JA. Offshore wind installation: Analysing the evidence behind improvements in installation time ; 2018.

Lee HW, Roh MI. 2018. Review of the multibody dynamics in the applications of ships and offshore structures. Ocean Eng.. 167:65–76.

M/S RAMFORM SOVEREIGN. 2008. https://www.skipsrevyen.no/batomtaler/m-s-ramform-sovereign/.

Major P, Skulstad R, Li G, Zhang H. 2019. Virtual prototyping: a case study of positioning systems for drilling operations in the barents sea. Ships and Offshore Structures. 14:364–373.

Maplesim. (last accessed 2020 Jan 05). https://www.maplesoft.com/products/maplesim/features/.

Marin simulator. (last accessed 2020 Jan 05). https://www.marin.nl/research/.

Maritime simulator systems. 2019. http://rules.dnvgl.com/docs/pdf/DNVGL/ST/2019-05/DNVGL-ST-0033.pdf.

Matlab simulink. (last accessed 2020 Jan 05). https://www.mathworks.com/products/simulink.html.

McGuire L. How emulation improves offshore operations. In: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering -- OMAE; Vol. 1; 11. American Society of Mechanical Engineers (ASME); 2019.

Ni labview. (last accessed 2020 Jan 05). https://www.ni.com/en-no/shop/labview/labview-details.html.

OFFSHORE FISH FARMING -- SalMar ASA. 2017. https://www.salmar.no/en/offshore-fish-farming-a-new-era/?tdsourcetag=s_pcqq_aiomsg.

OFFSHORE STANDARD DNV-OS-H101. DNV; 2011. http://www.dnv.com URL https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2011-10/Os-H101.pdf.

Offshore standard load transfer operations. DNV; 2012. https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2012-04/OS-H201.pdf.

Openfoam. (last accessed 2020 Jan 05). https://www.openfoam.com/.

Openmodelica. (last accessed 2020 Jan 05). https://openmodelica.org/.

Orcaflex. (last accessed 2020 Jan 05). https://www.orcina.com/SoftwareProducts/OrcaFlex/Features/index.php.

Osc. (last accessed 2020 Jan 05). https://www.osc.no.

Pan Y, Hildre HP. 2018. Holistic human safety in the design of marine operations safety. Ocean Eng. 151:378–389. https://www.sciencedirect.com/science/article/pii/S0029801817306443

Pixyz. https://www.pixyz-software.com/.

Recurdyn. (last accessed 2020 Jan 05). https://www.functionbay.org/multibody-dynamics-software/flexible-multibody-dynamics.html.

Rhein metall. (last accessed 2020 Jan 05). https://www.rheinmetall-defence.com.

Rhino 6. (last accessed 2020 Jan 05). https://www.rhino3d.com/.

Rtmaps. (last accessed 2020 Jan 05). https://www.dspace.com/en/inc/home/products/sw/impsw/rtmaps.cfm.

Recommended practice marine operations during removal of offshore installations, DNV GL; 2017.

Sadjina S, Skjong S, Pobitzer A, Kyllingstad LT. Seismic RTDT: Real-time digital twin for boosting performance of seismic operations. In: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering -- OMAE; Vol. 7A-2019. American Society of Mechanical Engineers (ASME); 2019.

Scilab. (last accessed 2020 Jan 05). https://www.scilab.org/about/features.

Shipx. (last accessed 2020 Jan 05). https://www.sintef.no/en/software/shipx/.

Sima. (last accessed 2020 Jan 05). https://www.dnvgl.com/services/marine-operations-and-mooring-analysis-software-sima-2324.

Simscale. (last accessed 2020 Jan 05). https://fhsim.no/.

Simsea. (last accessed 2020 Jan 05). http://simsea.no/simulators.html.

Skjong S, Rindarøy M, Kyllingstad LT, Vilmar Æ, Eilif P. 2018. Virtual prototyping of maritime systems and operations -- applications of distributed co-Simulations. J Marine Sci Technol. 23:1–17.

Solidworks. (last accessed 2020 Jan 05). https://www.solidsolutions.co.uk/solidworks/3d-cad/features/.

Star cmm+. (last accessed 2020 Jan 05). https://www.plm.automation.siemens.com/global/en/products/simcenter/STAR-CCM.html.

Str korea. (last accessed 2020 Jan 05). http://www.strkorea.co.kr/.

Sea transport operations (VMO Standard-Part 2-2). DNV; 2015. https://rules.dnvgl.com/docs/pdf/DNV/codes/docs/2015-10/OS-H202.pdf.

Taby J, Økland OD, Giertsen E, Ye N, Morgan M, Holden OM. On-board monitoring, analysis and decision support during offshore pipe lay operation. In: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering -- OMAE; Vol. 4; 2011. p. 335–341.

Tannuri EA, Martins GHA. Application of a maneuvering simulation center and pilots expertise to the design of new ports and terminals and infrastructure optimization in Brazil. 2018:1–18.

Time NP, Torpe H. 2016. Subsea compression -- Åsgard subsea commissioning, start-up and operational experiences. In: Proceedings of the Annual Offshore Technology Conference; Vol. 4; Houston. Offshore Technology Conference; p. 3212–3231.

Topham E, McMillan D. 2017. Sustainable decommissioning of an offshore wind farm. Renew. Energy. 102:470–480.

Transas. (last accessed 2020 Jan 05). https://www.transas.com/products/simulation.

Tree c. (last accessed 2020 Jan 05). https://www.tree-c.nl/.

Usp. simuladore full mission (last accessed 2020 Jan 05). http://tpn.usp.br/full-mission-telas/.

Vieira K. Oil & Gas UK Decommissioning Insight 2016 UK and Norwegian Continental Shelf; 2016. http://offshoredecommissioningconference.co.uk/wp-content/uploads/2016/07/Karis-Vieira-Oil-Gas-UK.pdf.

Voogt A, Wilde Jd, Dekker J. Integrating hydrodynamic and nautical studies for offshore LNG operations; 2014.

Vortex studio. (last accessed 2020 Jan 05). https://www.cm-labs.com/vortex-studio/software/.

Vstep nautis. (last accessed 2020 Jan 05). https://www.vstepsimulation.com/nautis-simulator/.

Wamit. (last accessed 2020 Jan 05). https://www.wamit.com/.

Wang AM, Chen R, He M, Zhu X, Xu J. Virtual Reality Simulations for Dynamic Positioning Floatover Installation. 2019. www.isope.org.

Wang AM, Pinkster J, Jiang X. Virtual Simulations of VLCC Class FPSO-SYMS Mating Operation; 2010. www.isope.org.

Xflow. (last accessed 2020 Jan 05). https://www.3ds.com/products-services/simulia/products/xflow/.

Yu Y, Duan M, Sun C, Zhong Z, Liu H. 2017. A virtual reality simulation for coordination and interaction based on dynamics calculation. Ships and Offshore Struct. 12:873–884.

Zhang X, Duan M, Mao D, Yu Y, Yu J, Wang Y. 2017. A mathematical model of virtual simulation for deepwater installation of subsea production facilities. Ships Offshore Struct.. 12(2):182–195. https://www.tandfonline.com/action/journalInformation?journalCode=tsos20

Zhen X, Vinnem JE, Yang X, Huang Y. 2020. Quantitative risk modelling in the offshore petroleum industry: integration of human and organizational factors. Ships Offshore Structures. 15(1):1–18. https://www.tandfonline.com/doi/full/10.1080/17445302.2019.1589772

20-sim software features. (last accessed 2020 Jan 05). https://www.20sim.com/features/.