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Final draft of

Application of Last Planner System to modular offshore wind construction

Authors:

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Application of Last Planner System to modular offshore wind construction

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Abstract

The focus of this study was the applicability of the Last Planner System (LPS) to modular offshore wind construction. Following a design science approach, a conceptual model for LPS adapted to modular offshore wind construction was developed, then refined and evaluated in a field study. The field study investigated was an offshore wind project in the Belgium sector of the North Sea. Theoretical knowledge from academics as well as practical experience from field experts allowed adjusting LPS to the context of modular offshore wind construction. The case study organization participated in the artefact development and evaluated its utility through implementation. In comparison to the original as-planned critical path method (CPM) schedule, implementation of the developed artefact reduced project duration by 21%. Since offshore wind projects have tended to substantially overrun their scheduled durations, 21% may understate the actual improvement.
Compared to current installation time within the industry the project made a 36% reduction, measured by average installation time per megawatt (MW). The developed LPS artefact contributes to the body of knowledge by adaptation of LPS to modular construction, and the evaluation shows its usefulness in the context of modular offshore wind construction.

Keywords

Application, design science, Last Planner System, modular construction, offshore wind project

1. Introduction

Within the construction management domain, offshore wind construction projects are still a novel topic. Lerche et al. (2019) found that these projects have previously used the critical path method (CPM) to plan their execution. Assembling prefabricated modules with an operational system considered similar to repetitive (Lutz and Hijazi 1993) and sectional modular construction (Peltokorpi et al. 2018). The standardization and work repetitions, are among the reasons that modular construction is considered to have planning and execution advantages over regular construction (O’Connor et al. 2015). Despite this, offshore wind projects have a legacy of cost and time overruns (Koch 2012; Sovacool et al. 2017). Within the construction domain, alternative planning methods to CPM have developed to change project management view points from transformational towards a flow orientation (Koskela and Howell 2002). Innella et al. (2019) revealed a broad range of lean methodologies that would benefit modular construction processes. Among these lean construction planning methods Last Planner System (LPS) is known to generate flow reliability through social interaction and commitment planning (Ballard and Tommelein 2016; Innella et al. 2019). Olivieri et al. (2019) supports this and expands how this improves production performance in comparison to those using CPM. Support for investigating alternatives to CPM in offshore wind is provided by Lacal-Aráñtegui et al. (2018) who argues that methods and procedures to install past generation of turbines are not necessarily well suited for the latest generation of offshore wind turbines. The literature review made it evident that few empirical studies so far have covered LPS implementation in modular construction or modular offshore wind construction.

The paper starts with introduction and framing of the problem, then the literature review describes the current planning methods in offshore wind, presents its limitations and introduces LPS. Then the method section describes the design science framework, how the objectives will be met and evaluated. This is followed by the case description and artefact development
including the theoretical adaptations. The achieved results from the implementation show the utility of the adaptation of LPS, the artifact, applied to an offshore wind project. The conclusion and discussion reveal the implication.

### 1.1 Framing the problem

The case organization requested a solution for planning and controlling the respective construction activities in modular offshore wind construction. A planner had arranged all the processes similar to that which Barlow et al. (2018) modeled with a detailed work break down (WBS) structure. During construction the planner would serve the role of progress reporter in the CPM based commercial software program (Primavera from Oracle). As this reporting was a contractual requirement no changes would be made to this arrangement. The project team, however, wanted to establish a look-ahead plan and change their operational planning from reactive to proactive. Browell et al. (2017) presents a similar perspective on current practices within offshore wind construction, managers generating the construction plan from day to day within each of their respective construction phases.

During this work a supervisor and a foreman described how planning was day to day. Questioning a pre-assembly supervisor with 8 years of work experience on the use of the scheduling software and asking “how do you plan today?”, he mentioned “because of the changing weather conditions it’s not worth to plan for more than the coming day”; a commissioning supervisor with 11 years of experience said “I make my transfer list the evening before, when the teams have reported in their status”. Both persons commented it represents common work practice. Stock-Williams and Swamy (2019) describe similar observations from other offshore wind operations. Similar statements arose while Lerche et al. (2019) investigated the applicability of location-based scheduling to modular offshore wind construction planning.

From an offshore wind project management perspective, Koch (2012) reported how offshore wind projects from 2004 to 2008 had an average time overrun of 45%. Sovacool et al. (2017) expanded this, finding offshore wind projects from 2000 to 2015 had an average cost overrun of 9.6% equivalent to 93 million US dollars (USD). Furthermore, finding that this was independent of the turbine MW output. Suggesting it is not what is being managed but the way it is being managed. Flyvbjerg (2011) would argue that often lacking commitment between multi-actor processes and interfaces are among the reasons for such delays or budget overruns, as they have potential conflicts of interest.
To meet these problems, the following objectives were developed as part of this design science project: 1) Develop an artefact based on the LPS approach to look ahead planning and commitment making among multiple actors and sub-projects, 2) implement and evaluate the artefact within the offshore wind project environment.

2. Background

2.1 Offshore wind energy projects

The high-level processes illustrated in Figure 1 shows the project phases which the individual sub-project moves through while the wind farm project develops. Top section of the figure reveals the relation between the offshore wind project phases and what Ballard and Tommelein (2016); Daniel et al. (2019) define as the master schedule in construction. This research focuses on the construction phases (pre-assembly, installation, commissioning) not considering design, production or later operations. The thin black lines in Figure 1 illustrates what Quandt et al. (2017) specifies as supplier-customer relationships between the project phases. Irawan et al. (2018) explains through a model how these materials flow from each individual manufacturing plant and shipping port to the pre-assembly port. The logistic network delivers prefabricated modules, that due to weight and dimensions are shipped from where they were fabricated to the pre-assembly port. Where Irawan et al. (2017) describes the harbor configurations, capacities and the logistic propositions prior to components being shipped out on purpose-built installation vessels (Barlow et al. 2014; Barlow et al. 2014; Paterson et al. 2018). Vis and Ursavas (2016) presents how installation is connected with pre-assembly, by describing installation compositions as A) “bunny”, B) “full rotor” or C) “separate”. Sarker and Faiz (2017) refers to these as follows: A) method 1, B) method 3, C) method 4. Further expanding with “method 2” which is A) with tower in 2 pieces and “method 5” which is C) with tower in 2 pieces. These extra variances of tower options seem less relevant unless the harbor or sail route has height restrictions. Similarly, B) would be liable to span restrictions in comparison to the rotor diameter. The quay area functions as a supermarket with buffer (Liker 2004), the CPM simulation though operates with predefined turnarounds defining the ready dates (Backe and Haugland 2017; Barlow et al. 2017; Muhabie et al. 2015; Paterson et al. 2018; Tekle Muhabie et al. 2018). These purpose built jack-up vessels carries batches of turbine composition sets offshore to their final location for assembly of the main interfaces (Barlow et al. 2018; Castro-Santos et al. 2018) by lifting like in modular construction (Taghaddos et
al. 2018). Commissioning arrives with smaller vessels to finalize the small interface connections, and set the turbines into operations.

The CPM schedules being predominate in offshore wind projects, only Alla et al. (2013); Barlow et al. (2018); Devoy McAuliffe et al. (2018); Guo et al. (2017); Ursavas (2017) considered all three construction phases together and viewed these as dependent input-output systems. Others mainly investigated the optimal vessel fleet and logistical plans for the offshore project phases (Besnard et al. 2011; Gundegjerde et al. 2015; Gutierrez-Alcoba et al. 2019; Gutierrez-Alcoba et al. 2017; Halvorsen-Weare et al. 2013; Raknes et al. 2017; Stålhane et al. 2019). All the simulations followed work breakdown (WBS) structures as described by Shtub (1988), organizing flow of activities inventory and materials for commissioning and operations. Multiple scenarios have been developed, and weather calculations made, only the value-adding activities considered in these input-output systems. According to Koskela (2000); Koskela and Howell (2002) the production system is viewed as transformational, dispatching activities inconsiderate of their readiness.

2.2 Critical Path Method

Within construction, critical path project planning has been a subject of interest since the early 1980’s when Cusack (1984) presented the use and limitations of CPM based mathematical models in this type of production system. A limitation was
identified; namely, that WBS predetermined activities are likely to be inaccurate and organizational performance only can be predicted in the short term. These predetermined activities are among the reasons that CPM schedules are regarded push planning (Hopp and Spearman 2001), pushing to execution without considering system readiness (Koskela 2000; Koskela and Howell 2002). Another reason, its management-as planning dispatching signals without commitment between actors (Johnston and Brennan 1996; Koskela and Howell 2002). Ballard and Howell (1994) would describe CPM scheduling as a traditional management practice, messages are dispatching which limits the communicational effect (Koskela and Howell 2002). As the planned activities are disconnected from the daily business (Johnston and Brennan 1996). Chua and Shen (2005) among others, recognizes that focusing on flow over transformation increases productivity, by solving constraints and reducing bottlenecks.

2.2 Last Planner System

In contrast to centralized predetermined CPM activities, Laufer et al. (1992) argues that application of short-term planning by foremen, supervisor quality circles and system analysis ensures flow. Last Planner existed as a term as early as 1994 (Ballard and Howell 1994), but has developed in stages, roughly matching the levels of planning, from bottom to top: commitment making and learning from breakdowns, look-ahead (make ready) planning, and phase scheduling. These commitment loops oppose the dispatching of activities seen with CPM. Ballard and Howell (1998) describe shielding of production by making activities ready in a look ahead process, generating a backlog of sound assignments and increasing the planning details gradually through the Last Planner System and part of why it is considered a pull system (Hopp and Spearman 2004; Kalsaas et al. 2015). LPS was developed by Ballard (2000) following a design science research process, developing a model with principles, elements and functions was developed for the construction domain (Ballard 2000; Ballard and Tommelein 2016; Daniel et al. 2019). The later utility of LPS in the construction domain has been established through multiple case studies (Abusalem 2018; Alsehaimi et al. 2014; Castillo et al. 2018; Daniel et al. 2015; Daniel et al. 2019; El-Sabek and McCabe 2018; Gao and Low 2014; Lindhard and Wandahl 2015; Nieto-Morote and Ruz-Vila 2012; Priven and Sacks 2016; Seppänen et al. 2010; Zaeri et al. 2017). For successful LPS implementation within the construction domain; in mega projects El-Sabek and McCabe (2018) argues that interface alignment, including communication between sub-projects and sufficient training are some of the key factors. Nieto-Morote and Ruz-Vila (2012) and Lindhard and Wandahl (2015) argue that lack of “coordination”, limits the LPS implementation in highly complex construction. Lindhard
and Wandahl (2015) emphasizes how this increases the importance of mindset and knowledge among actors involved. Daniel et al. (2019) supports this and adds how transparency, proactive involvement and preplanning also contributes to a successful implementation.

3. Method

This research project was inspired by Hevner et al. (2004), taking a pragmatic epistemological standpoint (Simon 1996). Figure 3 illustrates the research framework, following Hevner et al. (2004)’s design science approach, which both Baskerville (2008) and van Aken et al. (2016) recognized. The case describes the environment and is organized as Product, Process, Layout, Resources and Contract, which defines a production system (Schmenner 1993; Schmenner and Swink 1998). Where the literature review presented the knowledge base. The artefact and following implementation are the products of this design science project, and where it differs from action research (Järvinen 2007). As Gill and Hevner (2013) argue, the artefact evaluation confirms its applicability in the “real world”, making it reproducible in theory and practice (Flynn et al. 1990). In design science the rigor is demonstrated through the construction and evaluation of the designed artefact (Hevner et al. 2004; Peffers et al. 2007). Flyvbjerg (2006) supports this, arguing that single cases are generalizable based on case selection and experiment.

![Research framework](image)

Figure 2: Research framework. Inspired by Hevner et al. (2004)

The research method followed these steps:
1. Framing the problem for the organization, literature and industry,
2. conduct a literature review, investigate planning (Johnston and Brennan 1996; Koskela and Howell 2002) within both the construction and offshore wind domain, and
3. construction of the LPS artefact for the modular offshore wind construction, followed these steps:
   a. identify and verify a planning method that ensures flow reliability and commitments between project stakeholders.
   b. suggesting an artefact to the case organization,
   c. develop artefact and build the theory,
   d. organize production system to support artefact implementation, and
   e. define the objectives as performance measures that can evaluate this artefact.
4. Conduct longitudinal field study inspired by Yin (2014), and
5. evaluate the artefact utility and performance, compare measures with original CPM schedule.

While the artefact developed in this research may be applicable to modular projects of different types and communities, the focus of the validation was offshore wind projects. The proposed artefact could though be adapted to other modular project types and industries.

3.2 Data collection

The conducted qualitative data gathering is in Table 1 organized as “method” in left column and “comments” in right column. To address where and what, the comments for each method are structured as follows; 1) Artefact development, 2) implementation, 3) evaluation of the artefact. The primary data sources were obtained through physical access to the case organization and construction site from start to finish, enabling 8 months’ worth of data.

Table 1: Data collection methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field notes:</td>
<td>These notes include; observations, in-formal interviews and statements throughout the research project.</td>
</tr>
<tr>
<td>Observations:</td>
<td>Purpose was to understand; the project dynamic, the LPS artefacts and its fit in the environment. 2) 100 hours of pre-assembly work and planning observed, 80 hours offshore work and planning observed.</td>
</tr>
</tbody>
</table>
Workshops:  
1) Artefact workshop; introduce LPS, develop the model and production system.  
2) A total of four workshops, one conducted prior to each project phase: pre-assembly, loadout, installation and commissioning.  
3) Lessons learned workshop; post implementation and artefact evaluation.  

Focus groups:  
1) One focus group was used to finalize the model, provide inputs to LPS and organize the outer environment on-site.  
2) A focus group held for both the installation and commissioning unit plan.  
3) The focus group participating in artefact development, intended as evaluation committee.  

Interviews:  
(Semi-structured and open-ended)  
2) 19 formal interviewees were selected according to job position and experience within each specific construction phase: from pre-assembly; 1 site manager from the principal contractor, 2 site managers and 2 foremen from each contractor, and 1 tower engineer. From installation; 1 supervisor responsible for lifting and 3 technicians. From commissioning; 2 supervisors, 1 foreman and 2 technicians.  
2) 23 in-formal interviews were not registered as interviews, but rather captured in field notes as small quotations or statements.  

Note: 1) Artefact development, 2) implementation, 3) evaluation of the artefact.  

Secondary data sources were all obtained during and after implementation, these consisted of: logbooks, daily progress reports (including installation and commissioning lead time hours per unit), and weekly work plans (including Percent-Planned-Completed (PPC)) manually entered into a separate excel spreadsheet following Zaeri et al. (2017).  

3.3 Evaluation  
The evaluation was structured to measure the artefact performance in relation to the objectives, to meet first objective:  

1. the artefacts ability to incorporate look ahead planning, weekly work plans and adaption of existing theory.  
2. learnings from the implementation in accordance with LPS elements, functions and principles.  

To meet the second objective, a performance evaluation of the artefact within the environment is required. Evaluating phases separately first and later in combination:  

3. Artefact planning impact:  
   a. pre-assembly used PPC, as this is the genuine method for weekly work plan evaluation and indicator for commitments between on-site stakeholders (AlSehaimi et al. 2009; Ballard 1999; Ballard 2000; Lindhard and Wandahl 2015),  
   b. as neither installation or commissioning utilize the weekly work plans, these phases used the contractual hourly targets as performance measures, indicating the learnings between each unit completion.
4. Post implementation evaluate the overall project performance by comparing the CPM generated project schedule with the artefact impact to the as-built project schedule. For later comparisons purposes the measures selected were PPC and time as these are comparative across project types and industries. Besides the project time performance allows benchmarking with current offshore wind performance per turbine set (foundation and turbine) or MW (Koch 2012; Lacal-Arántegui et al. 2018; Sovacool et al. 2017).

3.4 Case – modular offshore wind construction

The selected case study is a modular construction project building an offshore wind farm with a total development investment of 1.1 Billion EUR. Ownership of the project is divided between different shareholders of an umbrella company (DEME 2019; Otary 2018). The final wind farm is located 42km off the coast, within the Belgium sector of the North Sea, and generates a total power output of 309 MW (Otary 2018). Each wind turbine is constructed according to the European machinery directive 2006/42/EC and delivers a 7 MW power output, stacked on monopile foundations which are piled at water depths between 22-36 m. Within field cabling of 33kilovolt (kV) and a 220kV export cable from the offshore substation to the coast (Otary 2018). The changes in voltage involved different regulations, 220kV power transmission from the mainland to the wind farm was provided by Elia (2019) a Belgium high voltage transmission company. 33kV was regional regulations, below 1kV categorized as low voltage and the separate energy transmission federation called Synergrid (2019) handles it.

The overall project is divided and contracted in 4 separate project packages providing special modules for the wind farm project, as shown in Table 2. Each package contract amount is above 100 million USD based on bid rounds. The turbine package was contracted by a yellow book from the Fédération Internationale des Ingénieurs Conseils FIDIC (2019) which is commonly known in construction as “Plant and Design-built” as part of the overall Engineering, Procure, Construction (EPC) contract (Yeo and Ning 2002). These characteristics, along the contract, international technical organizations and differences in regulations are what El-Sabek and McCabe (2018) categorize as an international mega project and program according to Flyvbjerg (2011); Flyvbjerg et al. (2003). Siemens had the turbine package manufactured in Germany and Spain. Further they engaged 2 lump sum subcontractors using green book contract form (FIDIC 2019), with their work scopes divided into onshore tower assembly by a Danish company and onshore transportation including lifting operations.
by a British company. Changes to the original lump sum scope for both prime and sub-contracts require variation orders signed by the main contractor and employer. The sub-project “cabling” is the only commodity which does not move through a pre-assembly phase.

Table 2: Contractor data. Source: DEME (2019).

<table>
<thead>
<tr>
<th>Sub-project or package</th>
<th>Main contractor</th>
<th>Country</th>
<th>Scope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundation &amp; infield cabling</td>
<td>DEME Group</td>
<td>Belgium</td>
<td>Design, Supply, transport and installation</td>
</tr>
<tr>
<td>Turbine</td>
<td>Siemens</td>
<td>Germany &amp; Spain</td>
<td>Design, Production, Supply, installation and service</td>
</tr>
<tr>
<td>Offshore substation</td>
<td>STX Europe</td>
<td>Norway</td>
<td>Design and Supply</td>
</tr>
<tr>
<td>Export cable to coast</td>
<td>ABB</td>
<td>Sweden</td>
<td>Design and installation</td>
</tr>
</tbody>
</table>

The harbor location for the pre-assembly was predetermined during the contract negotiations. Later the project organization designed a layout for component staging and loadout as described by Irawan et al. (2017) and shown in Figure 3. The quay surface load bearing capacity impacted the choice of crawler crane and tower package orientation which supports the parameters presented by Irawan et al. (2018). Figure 3 shows Oostende, Belgium in a satellite image with the actual turbine components positioned on the harbor front.
Figure 3: Oostende harbor layout from Google (2019) reveals the wind turbine construction phase.

The modular components were received at the geographical position B2 in Figure 3, sharing the smaller cranes and transport equipment with the production part. Position B3 illustrates the tower assembly area with a maximum capacity of 8 towers erected defined by the of vertical tower assembly adapters also referred to as tower pack. B3 also represents the loadout area for the installation vessel. Position L1 is storage area for nacelles, L2 is for blades and L3 horizontal storage of tower sections. Commissioning had a storage facility in the L1 area in direct connection with berth B1 where the commissioning vessels conduct daily access and egress.

The turbine package organization got engaged during contract development and consisted of a temporary project management team working week days only. This team was fixed throughout design, procurement and construction phases. The project team built their master schedule according to the contractual CPM schedule and its sub-project milestones which are: contract development (task A: 51 weeks), design (B: 98 weeks), manufacturing (C: 86 weeks), site mobilization (D: 17 weeks), pre-assembly and installation (E: 35 weeks), and commissioning and take over (F: 33 weeks). The construction organization was formed for construction alone (D,E,F), white and blue collars working 12 hour shifts in 14-day rotations. Each of the 3 phases; pre-assembly, installation and commissioning had a designated site manager. Each
team, consisting of a foreman and assigned technicians, was established for mechanical, lifting, and electrical activities. The electrician team was segregated into low and high voltage due to legislative and supervision differences. The turbine package sourced specialized technicians from internal resource pools for pre-assembly nacelle and blade work, plus the offshore installation and commissioning activities.

4. LPS artefact - Modular offshore wind construction

4.1 Inner environment

The case organization divided the construction phases as follows; “pre-assembly” and “installation” as interdependent systems, with “commissioning” as a separate dependent system. The masterplan for the case study project was predefined according to the EPC contract, with predetermined dates captured on a CPM schedule. Due to vessel day rates the installation vessel chartering period determines the schedule start. This connection is in Figure 5 illustrated by thick dashed lines, from the “master schedule” to both “installation” and “production”. Project start is then calculated by determining how many days prior to “installation” the modules are required for completion of; “production”, transport and “pre-assembly”. Pre-assembly site mobilization being a precondition for the operations has to start earlier than assembly activities, ensuring that the harbor facilities can accommodate the components and processes (Irawan et al. 2017). Solid lines in Figure 5 represent product movements from “production” to “complete turbine modules”. Relating productions with the weekly meeting structure (Look-ahead / Weekly) and how these are connected. Pre-assembly functions as the LPS process (Ballard 2000) for the installation and commissioning, transforming the modules from “can” into “will”. The “should” look-ahead was every 8-weeks for the pre-assembly and commissioning, as the case study logistic network had an average of 8-weeks delivery time. The look-ahead process for the installation phase was determined not applicable, as this phase received modular components from the pre-assembly and once their initial preparation phase was completed only had to sustain readiness. The daily operations meetings for pre-assembly involved all site stakeholders adjusting operational performance in alignment with obstacles and challenges. The offshore daily operations meeting was involving all stakeholders and marine coordinators, ensuring valid work permits, confirming current vessel positions in the field and progress. Both daily operation meetings were intended to confirm clearance of obstacles, follow up on operations and make adjustment to the plans in case the weather had changed according to forecasts for the coming day. It was recognized during
the initial workshops with the project team that technical and location sequences for modular installation and commissioning, made a week plan less obvious for these processes. Instead of following Ballard and Howell (1994) the module unit plans were sequenced per unit, independent of the weekly work plans. Inputs from past utilizations of LPS in construction led to this framework (Figure 4), ensuring that artefact development and implementation would experience the least possible friction in the environment. As illustrated in Figure 4 “pre-assembly” and “installation” shared weekly work and look-ahead meetings, meaning that also preparation and obstacle lists were shared. Commissioning instead communicated it’s look-ahead to the pre-assembly weekly work plans.

![Diagram of Modular offshore wind construction LPS framework.](image)

Figure 4: Modular offshore wind construction LPS framework.

To support the application of the artefact in the outer environment, the authors presented the 5 elements, 8 functions and 12 principles from Ballard (2000); Ballard and Tommelein (2016) in a workshop involving managers and foremen from the project team. The 5 elements of Last Planner have been described in detail by Ballard (2000); Ballard and Tommelein (2016); Daniel et al. (2019); Viana et al. (2017). For the artefact, elements 3 and 4 were adjusted to accommodate the module installation and commissioning;
1. Master planning / milestone planning
2. Collaborative programming / phase planning
3. Make-ready planning, organized by module installation sequence
4. Weekly and unit work plans
5. Measurement and learning

Functions 1, 4, 5 and 8 were modified with the project team to accommodate the modular construction activities offshore as these have predefined technical dependencies, which Peltokorpi et al. (2018) also recognizes for sectional architectural interfaces.

1. Specifying what tasks should be done when and by whom, from milestone to phases between milestones, to processes within phases, to operations within processes, to steps within operations. Following technical sequencing for the modular installation and commissioning.
2. Making scheduled tasks ready to be performed.
3. Replanning/planning to complete, to achieve project objectives. Module unit plans to be generated prior to construction.
4. Selecting tasks for hourly, daily and weekly work plans—deciding what work to do next, the modular element work planned per hour not daily or weekly.
5. Making release of work between specialists and phases reliable.
6. Making visible the current and future state of the project.
8. Learning from plan failures, following the Deming cycle Plan-Do-Check-Act (PDCA) (Deming 2000).

Besides the 5 elements and 8 functions, 12 principles have been well described by Ballard (2000); Ballard and Tommelein (2016). For this framework, the principles; 3,4,8,10 and 11 were adjusted and applied for the modular construction:

1. Keep all plans, at every level of detail, in public view at all times.
2. Keep master schedules at milestone level of detail.
3. Plan in greater detail as the start date for planned task approaches. Unit plans made available latest at first make-ready meeting.
4. Produce plans collaboratively with those who are to do the work being planned. For unit plans, installation and commissioning team members are to formulate a standard workflow per unit.

5. Re-plan as necessary to adjust plan to the realities of the unfolding future.

6. Reveal and remove constraints on planned tasks as a team.

7. Improve workflow reliability in order to improve operational performance.

8. Don’t start tasks that you should not or cannot complete. Commit to perform only those tasks that are properly defined, sound, sequenced and sized. All tasks related to module installation and commissioning has to be sound before unit execution starts.

9. Make and secure reliable promises, speak up immediately should you lose confidence that you can keep your promises (as opposed to waiting as long as possible and hoping someone else speaks up first).

10. Learn from breakdowns (unintended consequences of actions taken). Feed into the 5th principle, that re-planning should occur when obstacles (6th principle) or challenges are encountered that affects the flow.

11. Underload resources to increase reliability of work release. Secure the specialist for module installation and commissioning in adequate time.

12. Maintain workable backlog; a backlog of ready work (tasks ready to be executed) to buffer against capacity and time loss.

4.2 Organizing the outer environment

The pre-assembly workable backlogs presented in Figure 5 reside in different geographical areas of the harbor site without limitation of technical dependencies or installation sequence. The backlogs represent activities which are still not made ready for production. Pre-assembly look-ahead process protects the installation sequence by having a buffer capacity of main components, maintaining a backlog of three ready loadout batches on quay side. Based on the test and inspection, a punch list is developed which generates the rework backlog intentionally resolved prior to loadout. The installation vessel operates in batches, the pre-assembly is structured to produce those batches according to “separate part” composition (Vis and Ursavas 2016). Their activities have hard technical dependencies and the phases are interdependent as the installation sequence and timing provides the system pull. From the repetitive modular installation, pre-assembly is provided a pace of units required per week. It determined the turnaround rate between harbor visits and when a loadout was to be expected
which could then be inputted into the weekly work plans. For installation activities the teams generated repetitive single module plans, ensuring that activities, resource and equipment was organized per hour. These plans could then be repeated for each module assembled at the individual locations and learnings would be captured after each successful completion of installation. Their preparation would then ensure that information, resources, equipment, and tools would be ready. As these preconditions were in a state of maintenance between module cycles, technical breakdowns would require repair or replacement. From a weekly work plan perspective, commissioning follows the installation sequence and their pace input also alerted commissioning about the level of completion for them to access the main modules assembled. The commissioning unit plans could also be repeated for each module pulled from the “backlog of installed modules” at the individual locations and learnings would be captured after each successful completion. The offshore commissioning activities for the modular units are predetermined. The technical product dependencies required commissioning activities to follow a certain sequence, followed by a test period ensuring the technical capabilities of the turbine. Duration of the test and approval parameters are contractually determined, along with inspections being another obligation for the contractor. Based on potential findings, a punch list is developed which generates the rework backlog. Their look-ahead process would similarly follow 8-weeks cycles and ensure; information, spare parts, resources, equipment and tools being ready. As these preconditions were in a state of maintenance between module cycles, technical breakdowns would require repair or replacement. A flow diagram for pre-assembly, installation and commissioning is shown in Figure 5. The lines representing the flow between activities, where the activities are inseparable this illustrates technical dependencies. These are for installation defined by the natural laws of gravity and for commissioning the product system design.
4.3 Implementation – interface between inner and outer environment

The authors explained how the success factors required “top management support”, “involvement of all stakeholders” and “communication”. The rules for communication in the case study project were agreed as the artefact was developed, utilizing process maps e.g. Figure 5 as part of the presentation material for stakeholders and for the individual team members who were not part of developing the modular unit plans. The coordination and commitment making was addressed through implementation agreements, and also through training during the onboarding of technical and non-technical resources onto the construction site. Pre-work workshops were conducted 8 weeks before the start of each project phase. These workshops were organized around these topics: why LPS, weekly meeting structure, expected behavior, make ready process and preconditions. Besides these steps there was a project specific process mapping with the operational teams, with process engineers engaging in question and answers regarding the design and equipment. One week before each offshore construction phase, another workshop was held to engage stakeholders from both port and vessels. The vessels illustrated their modular process plans on post-it labels, identifying risks and opportunities, rock drills were initiated for components at loadout and supply runs for commissioning. This was to illustrate the processes for the managers and later enable dry runs
where operators walked through the geographical positions and talked through interfaces. Table 3 illustrates the learnings from the implementation are numbered as linkage to the adapted elements, functions and principles.

Table 3. Interface learnings between inner and outer environment.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Learnings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements</td>
<td>1. The master schedule was based on the contractual “should” promises.</td>
</tr>
<tr>
<td></td>
<td>2. As construction was based on modules, the project team expressed their plan of work in what modules “can” be done (fabricated, preassembled, installed, tested, etc.) at specific times during the project.</td>
</tr>
<tr>
<td></td>
<td>3. The backlog of “will” activities for installation and commissioning was pulled piecemeal into the “make ready” process in a predefined sequence, pre-assembly processes allowed logical sequencing.</td>
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<tr>
<td></td>
<td>4. The unit work plan required all activities be ready simultaneously. Technical dependencies did not allow a backlog or pending tasks within the plan.</td>
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<tr>
<td></td>
<td>5. The “did” category with measurement and learning became integrated with Deming (2000) cycles, capturing repetitive adjustments of the module specific plans.</td>
</tr>
<tr>
<td>Functions</td>
<td>1. Following technical sequencing for the modular installation and commissioning, in this case it meant organizing operations according to the model for the outer environment (Figure 5).</td>
</tr>
<tr>
<td></td>
<td>2. All phases followed the making ready processes showed in Figure 4, module installation and commissioning required pre-condition to be maintained between the units.</td>
</tr>
<tr>
<td></td>
<td>3. The module unit plans generated prior to construction, were as the modular construction progressed expected to be repetitive, plans were adjusted to achieve project improvements and objectives. The adjustments of these functions were the level of details; i.e., planning for individual technicians on hourly base per module throughout its level of completion. Technical restrictions limited flexibility in re-planning and hence in recovering from delays.</td>
</tr>
<tr>
<td></td>
<td>4. The increase in accuracy was necessary due to: 1) contractual installation times measured in hours, 2) the large financial impact from equipment and vessels, 3) enabling the feedback loop between units.</td>
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<tr>
<td></td>
<td>5. Release between the sub-project caused issues, aligning between the phases, despite their meeting structure was being followed. E.g. module installation commitments failed due to weather and vessel constraints, negatively impacting pre-assembly and commissioning as the pace for their preparation or take over times were inconsistent.</td>
</tr>
<tr>
<td></td>
<td>8. Learning from using PDCA, all obstacles and opportunities were captured in excel sheets, Pre-assembly and installation shared, commissioning had an individual sheet. This helped solving adjustments of the unit plans continuously.</td>
</tr>
<tr>
<td>Principles</td>
<td>3. The unit plans were required prior to construction, ensuring that resources, tools and equipment was made ready. The foremen were proactively engaged in making tasks ready, weekly and unit work plans. For the offshore module readiness, it meant that the making ready was prioritized in accordance with the installation sequence.</td>
</tr>
<tr>
<td></td>
<td>4. The meeting structures made the foremen and managers meet, adjust to mitigate weather and unforeseen events. The daily operations meetings ensured a constant following up on progress and the made commitments.</td>
</tr>
<tr>
<td></td>
<td>5. Weekly work plans participants gained confidence in each other’s commitments gradually, problems were actively solved and mitigated. The unit plans followed the PDCA cycle between each completion, ensuring learnings were captured and a total of 6 revisions of the initial unit plans.</td>
</tr>
<tr>
<td></td>
<td>8. All tasks related to a module installation and commissioning had to be sound before start as it’s technical dependencies doesn’t allow making do (Koskela 2004).</td>
</tr>
</tbody>
</table>
10. The feedback loop was established to 5th and 6th principle, supporting the re-planning and revisions of weekly and unit work plans. The learnings about flow conditions not met or failing are captured in percentages as part of the achieved results for each phase.

11. Certain specialist roles were requested early due to the international resource pool and necessity for completion of the module installation and commissioning. Throughout the implementation and the construction phases no changes were made to the original input of resources such as workers.

5. Achieved results

5.1 Pre-assembly performance

During the project pre-assembly, the following PPC measures were generated based on the all of activities which were planned and realized from calendar week (CW) 11 to 34, differentiating from the original scheduled finalization at CW42. The summaries are presented in Figure 6 as total values summarizing PPC from different subcategories as; towers, nacelles, blades and site (Figure 5). Tower activities included: handover, preparation, assembly, lifting, paint, inspections, mechanical and electrical completion. Site related activities included: transport on site, logistics of main components to site, certifications, maintenance and other preparation works. The nacelle subcategories included preparation and inspection. Blades was not further broken into subcategories. The weekly average PPC for the entire period (CW 11-34) was 68.1%.

That both PPC and number of tasks increases indicates an increase in reliability and commitment between the teams. Some of the reasons for PPC failures were distributed as follows; 38% previous task, 10% equipment, 10% location, and 10% weather. The interdependence between pre-assembly and installation was reflected in CW23; the tower pack being full and all nacelles being ready for loadout, but the workable backlog of activities was on hold until the installation vessel returned. As there was no pull from the installation vessel the pre-assembly activities dropped. In addition, a severe lost time case on the installation vessel in CW23 affected pre-assembly by drastically lowering their PPC with 40% points as crises counselling involved all teams.
Figure 6: Pre-assembly PPC measures compared with the number of tasks each week.

5.2 Offshore performance

Ballard and Howell (1998) and later Liu et al. (2011) showed a relation between resource productivity and planning reliability through PPC even though they were measured differently. In figure 7, the y-axis shows hours finalizing installation and commissioning, displaying a maximum of 92 hours, and a minimum of 24.1 hours, and the x-axis shows each individual turbine, in average 4.19 days per turbine. For each module, the activities were measured in hours from “tower installation” to “finalization” (Figure 5); each module lead time included breakdown of equipment, deviations and weather. For commissioning, the activities for each individual turbine (Figure 5) are measured from “installation backlog” to “in operation”. For these performance measures, sailing time, test periods and inspections were filtered out. This is reflected in a declining lead time linear trend from 52 to 28 hours a 53% reduction. The outliers above 30 hours represented 26% of the total installation population, 72% of these were caused by wind above the accepted limits or equipment breakdown. For commissioning 62% were related to troubleshooting of previous tasks, 22% missing or faulty parts, reaming deviations were related to competences and system failures before the test.
5.3 Post implementation

The performance measures only reveal the individual phases, whereas Figure 8 compares the as-planned CPM schedule and as-built. The schedule in Figure 8 “light” color being reference to the as planned where the “dark” shows the as-built registrations of the project phases, revealing how design and manufacturing utilized all available time. Whereas the pre-assembly with installation finalized in a month earlier than as planned, the commissioning and take over finished 1.5 months earlier. In comparison to the original CPM schedule, the reduced construction days for pre-assembly and installation was equivalent to a 25% reduction, where commissioning achieved a 28% reduction and overall achieved a 21% reduction.
Figure 8: Project turbine contract schedule comparing as planned (light grey) with as built (dark grey).

6. Conclusion and discussion

The current offshore wind project planning practices revealed CPM to be the dominant planning method, leading to cost and time overruns. As Sovacool et al. (2017) argues, it is not the managed but how it is managed which leads to current performance.

The developed artefact meets the first objective, as it incorporates commitment making, organizing the LPS planning structure with adaptation of the principles, functions and elements. The technical dependencies are seemingly what differentiates the modular construction from regular constructions (Peltokorpi et al. 2018), and what would make the artefact applicable to alternative modular construction types. But it would require further research to fully understand the artefacts extended applicability. Further a new prescriptive model for the outer environment enabled the implementation and ensures the artefact relevance to future offshore wind projects. Similarly, Ballard (2000); Ballard and Tommelein (2016) earlier prescribed the LPS model and its usage within construction, as a treatment for CPM shortcomings.

Pre-assembly showed that in the period after CW23, PPC (CW 23-34) averaged 78.2%, according to Lagos et al. (2019) 77% was considered average among 50 construction projects. For offshore the linear regression revealed a 53% improvement overall for the unit plans, following what Thomas et al. (1986) argues to be the “exponential model”. The performance measures could be reflections on technician learning curves due to repetitive work, it could also be a product of the work flow reliability (Liu et al. 2011). Or modular repetition in general, O’Connor et al. (2015) though sees its planning among the advantages for module installation and commissioning. But as Sovacool et al. (2017) argues, the past project performances have been independent from what is being managed and could instead be related to how it has been
managed. We interpret the performance improvements here, to be products of the alternative planning method, not learning curves from module repetition alone.

Furthermore, the offshore performance showed an average of 4.19 days per turbine. Adding the average 1.33 days per foundation (Lacal-Arántegui et al. 2018Table A1) with the turbine achievements would be 5.52 days per set or 0.75 days per MW. Table 4 compares the average of 9 wind farm with construction start 2016 to 2017 (Lacal-Arántegui et al. 2018) with the post implementation results, the 14% reduction per turbine set and a 36% reduction per MW reveals a high relevance for the offshore wind projects.

Table 4: Benchmarking results with average installation days per - turbine set (foundation and turbine) and per MW.

<table>
<thead>
<tr>
<th></th>
<th>Per turbine set</th>
<th>Per MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lacal-Arántegui et al. (2018 Table 4)</td>
<td>6.44</td>
<td>1.17</td>
</tr>
<tr>
<td>Our results</td>
<td>5.52</td>
<td>0.75</td>
</tr>
<tr>
<td>Reduction</td>
<td>14%</td>
<td>36%</td>
</tr>
</tbody>
</table>

Where the overall achieved 21% reduction seen in relation to mega project management as both Flyvbjerg (2011) and Koskela and Howell (2002) displays that management-as organizing with commitments between actors and interfaces to some extend have been met. The artefact does not reject issues that El-Sabek and McCabe (2017); El-Sabek and McCabe (2018) showed but faced these along with others during the international mega project. The artefacts relevance for other international mega project lies with a model of the production system, clear understanding of the relation and interfaces between the LPS theory and practice. Both Lindhard and Wandahl (2015); Nieto-Morote and Ruz-Vila (2012) argued that management involvement, training and communication would be key reasons for successful LPS implementations. The workshops prior to each project phase were means for this, involving all stakeholders internally and externally (including managers, technicians, operators, and engineers).

Meeting the objectives was part of what Hevner et al. (2004) would argue as relevance, the artefact itself was the solution as it proved an more efficient planning method than current practice. The artefact implementation revealed its fit with the
environment, further its performance within the environment showed how it was a better solution for managing through organization instead of managing as planning (Johnston and Brennan 1996; Koskela and Howell 2002).

The objectives and achieved results clarify that LPS is applicable in offshore wind construction as an alternative to CPM planning. This contributes to the body of knowledge within the offshore wind domain by introducing and testing a new model. The adaptation of the LPS principles, elements and functions contributes to the modular construction engineering and management domain and literature. The learnings from the breakdowns are not discussed in detail here as these will be topic for future research. Further research would be required to understand if this artefact would be applicable in other modular construction industries.

Data Availability Statement

Data gathered, developed or analyzed during the project are available from the corresponding author by request.

Information about the Journal’s data-sharing policy can be found here: https://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263

7. Reference list


