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Published in:
Energy Strategy Reviews

DOI (link to publication from Publisher):
10.1016/j.esr.2021.100794

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Lerche, J., Lindhard, S., Enevoldsen, P., Velaayudan, A., Teizer, J., Neve, H. H., & Wandahl, S. (2022). What can be learned from variability in offshore wind projects. *Energy Strategy Reviews*, *39*, Article 100794. https://doi.org/10.1016/j.esr.2021.100794

Energy Strategy Reviews 39 (2022) 100794

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

What can be learned from variability in offshore wind projects

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ARTICLE INFO

Keywords:
Flow
Offshore wind
Productivity
Process-time
Variability

ABSTRACT

The focus of this study was to learn from the operational variabilities in offshore wind projects by investigating the overall delays in offshore wind projects related to arrival time (flow) or job time (process-time) variability. This research was motivated by the general understanding that flow variability is dominant within the offshore wind domain. The case study presented is based on 183,197 historical data-points from six different cases, the selection of cases was based on overall controllable project features. The findings reveal that from a variability perspective onshore performs better than offshore. The distribution also reveals that the process-time variability is dominant for both the onshore and offshore assembly location. This indicates that the offshore wind project variabilities are controllable and oppose the general understanding within the body of knowledge, however, further research would be required to understand the probable causations. The analysis and its results can be used for later predictions of project schedule outcomes or as explicit external knowledge for comparison. The results of this research project are relevant to both academics and practitioners, not only in offshore wind projects, but also onshore wind and other operations handling remote assembly locations.

1. Introduction

Production stability can be defined as “an even swift flow of transformations with limited or controlled variability” [1], which is essential for the successful delivery of products independent of the product being a car, a building, or a wind farm. Factory Physics by Hopp, Spearman [2] supports this definition and argued that productivity is achieved by reducing variability. Indifferent to the production system, variability is argued to reduce productivity, which Al-Momani [3] supports from a project delay perspective, arguing that variability can predict changes in time. Finally, Lindhard, Hamzeh, Gonzalez, Wandahl, Ussing [4], found that the negative effects of variability can be reduced by simplifying the sequence, keeping the number of parallel activities at a minimum, and constantly updating the schedule.

Academics [5–8] and decision-makers, such as project managers [9–14], have for decades had a focus on solving the ‘productivity’ problem and gaining control over the variabilities. In both offshore wind and other renewable energy domains, the critical path method (CPM) is found to be the dominant planning method to handle this [15–19]. By applying CPM based models, studies investigated how to reduce the project schedule [20–22]. The referenced CPM models predict the productivity outcome of processes measured in time and thereby estimating cost. A reason for using CPM could be that the contractual schedule in offshore wind projects as in other industries is based on CPM [23], but this is not further pursued here. Despite past planning efforts, Lacal-Arántegui, Yusta, Domínguez-Navarro [24] still question whether current project practices are the means for increasing productivity in future wind projects. This, however, remains an unanswered question from academia as well as practitioners in the field. This study conducts a literature review supported by an extensive empirical data analysis, in order to provide a response to the apparent lack of investigation and consensus on variabilities in offshore wind projects.

From a project management perspective, CPM was criticized by Koskela, Howell [25] as obsolete, as it is based on activity dispatching

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; CPM, Critical Path Method.

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https://doi.org/10.1016/j.esr.2021.100794
Received 10 September 2021; Received in revised form 22 November 2021; Accepted 3 December 2021

independent of system or receiver readiness. Koskela [26] encouraged the construction management community to change or expand their world view by seeing management-as organizing instead of planning alone. This further entails that assumptions are crucial to mitigate system uncertainties when planning, estimating cost [27,28], or applying probabilistic methods such as Bayesian networks [29–33]. Assumptions are often based on empirical findings, past explicit knowledge [31,34], or expert analysis techniques [35]. Furthermore, no empirical studies have previously sought to explore how the on-site assembly changes in locations affect the variability in offshore wind projects. This research project is relevant to both academics and practitioners, not only in offshore wind projects, but also onshore wind or other projects handling remote assembly locations.

2. Theorizing project-production planning within offshore wind

The body of production and construction-related knowledge has so far focused on the principles behind variability in an assembly line or project-based production. The scope of this review is to understand the project-production planning within offshore wind projects and the variability for its on-site assembly, if any. Especially understanding variability and on-site assembly transition to remote locations, as these are novel topics within the project and renewable energy domain.

2.1. Production system variability

The occurrence and distribution of variabilities have concerned both managers within production and construction throughout the decades. Variability in its general terms can be divided between “flow” and “process-time”, which have been of interest within both construction and production literature. Both variabilities are seen as reasons for reduced productivity or constraints, as Goldratt [36] described it. In short, the workstation starves or its performance differs from the ideal due to variability. Hopp, Spearman [2] address activity variability from a transformational perspective. This is important as it depicts that offshore wind project planning is dominantly transformational oriented [17,18]. Hopp, Spearman [2] understanding of “flow” and “process-time” variability in relation to the activities is elaborated as:

A planned activity or transformation process is about to commence:

o The activity can start.
o The activity/job fails to start or reach the workstation (flow variability).

A transformation process during execution:

o The activity completes on time.
o The transformation process is not completed on time (process-time variability).

However, Hopp, Spearman [2] dominantly investigated products moving through workstations. In construction, the building with its locations is the final product, and trades are perceived to be workstations that in a given order, move through the locations [26,37]. For this particular research project, the investigation is a combination of “flow” and “process-time” variability from Hopp, Spearman [2], and Koskela [26] understanding of assembly locations.

2.2. Offshore wind project-production

Delivering an offshore wind project consists of multiple phases as described by Lerche, Neve, Ballard, Wandahl, Gross [18]; modules are delivered to an onshore pre-assembly harbor area where the modules go through a transformation process [22,34,38]. The modules are prepared onshore in various compositions; “bunny ear”, “rotor star” and “separate parts” which relates to how the tower, nacelle, and blades are assembled during installation. The tower sections are either partially or fully assembled during the onshore process. The onshore output is then batched for the installation vessels to pick up and transport to the offshore locations. The offshore transformation is then started by the installation crane vessel, which assembles the main components (a full tower, nacelle, and three blades) for one turbine at the time [39–41]. Afterward, commissioning teams arrive by commissioning vessels and finalizes the offshore transformation process turbine by turbine at their offshore location. For floating wind, the sub-processes would all be conducted within the proximity of the onshore assembly location [43,44]. Fig. 1 illustrates the pure assembly structure [42] and its main transformation processes “onshore” and “offshore”. These input-output transformations summarize the sub-processes as described above, onshore representing pre-assembly, where offshore represents the installation and commissioning. The arrows represent the queuing functions of moving and waiting, where each of the project phases is finalized with an inspection of the work. Despite multiple studies expanding on the project phases individually or in combination, few, if any, have yet expanded the understanding of variabilities in projects with multiple on-site assembly locations.

2.3. Offshore wind project variability

The offshore wind project variabilities considered here are in relation to on-site assembly and the transformation processes. Table 1 illustrates how planning and management literature for renewable energy projects with on-site and remote locations (e.g., offshore wind projects) considers variability as part of their planning, revealing that focus has been on flow variability. The categorizations were as follows; the variability “flow”, where tasks can commence based on the prediction of timeslots identical to the activity duration e.g., identifying weather windows with adequate time for activity completion utilizing queueing theory or reducing distances by applying graph theory. The variability “Process-time” where the planning or calculations investigating the ideal activity durations e.g., by applying random variation through stochastic predictions. For those with combined locations, both project locations where considered and followed similar variation segregation as described above. Both pre-assembly and a maintenance station are considered onshore, both providing materials for the offshore or remote location assembly operations. But as Table 1 also revealed, little knowledge exists of the onshore location or its variabilities.

2.3.1. Offshore wind project overall variations

To further understand the causes of variability in a production system, Hopp, Spearman [2] expanded by investigating different variation factors such as natural, recycle, pre-emptive, and non-pre-emptive outages. Koskela [26] defines variations as preconditions, which are controllable material flows (e.g., locations, resources, equipment, etc.) and immaterial flows (e.g., information, documentation, etc.) [77–79]. To understand the offshore wind project manager’s levers, three key variations were identified in offshore wind literature: 1) natural variation, 2) input variation, and 3) location variation. These were also utilized for case selection.

1) Natural variation, Enevoldsen, Xydis [80] elaborated on how the offshore wind turbines consistently have been developing in size, dimensions, and power output since the first commercial projects in the late 1990s, which ultimately impacts the natural variation, e.g., tolerances, weight, and dimensions. From a physical perspective, combinations of weight and dimension would be deterministic for both harbor and installation vessels, as these carry the modules in predetermined batches. But from an onshore assembly perspective, Irawan, Song, Jones, Akbari [81] focused on module dimensions. Weight is neither a topic for the onshore or offshore part of the project, e.g., Barlow, Tezcaner Öztürk, Revie, Akartunalı, Day,

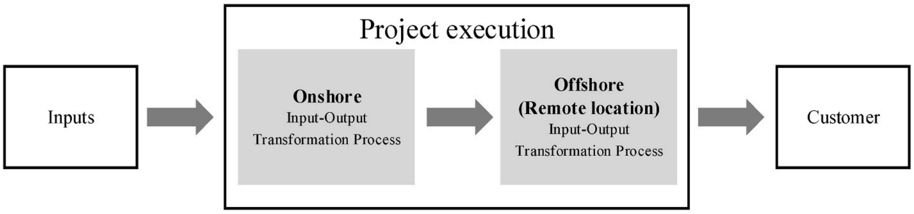

Fig. 1. Offshore wind turbine construction project execution model.

Table 1
Project management literature with multiple assembly locations.

	Onshore (On-site location)	Offshore (Remote location)	Onshore & Offshore
Flow variability		Kerkhove, Vanhoucke [20]’Nielsen, Sørensen [30]’Barlow, Tezcaner Öztürk, Revie, Boulougouris, Day, Akartunalı [39]’Vis, Ursavas [40]’Scholz-Reiter, Heger, Lütjen, Schweizer [45]’Alla, Quandt, Lütjen [46]’Halvorsen-Weare, Gundegjerde, Halvorsen, Hvattum, Nonås [47]’Sperstad, Halvorsen-Weare, Hofmann, Nonås, Stålhane, Wu [48]’Dinwoodie, McMillan [49]’Dalgic, Lazakis, Turan, Judah [50]’Dalgic, Lazakis, Dinwoodie, McMillan, Revie [51]’ Shafiee [52]’Petersen, Madsen, Bilberg [53]’Gutierrez-Alcoba, Hendrix, Ortega, Halvorsen-Weare, Haugland [54]’Leontaris, Morales-Nápoles, Dewan, Wolfert [55]’Schrotenboer, Ursavas, Vis [56]’Stålhane, Halvorsen-Weare, Nonås, Pantuso [57]’Stock-Williams, Swamy [58]’Catterson, McMillan, Dinwoodie, Revie, Dowell, Quigley, Wilson [59]’Gintautas, Sørensen [60]’Paterson, D’Amico, Thies, Kurt, Harrison [61]’Taylor, Jeon [62]’ Ursavas [63]’Backe, Haugland [64]’Raknes, Ødeskaug, Stålhane, Hvattum [65]’Kovács, Erdős, Viharos, Monostori [66]’Dinwoodie, Endrerud, Hofmann, Martin, Sperstad [67]’Irawan, Ouelhadj, Jones, Stålhane, Sperstad [68]’Muhabie, Caprace, Petcu, Rigo [69]’Stålhane, Vefsnmo, Halvorsen-Weare, Hvattum, Nonås [70]	Barlow, Tezcaner Öztürk, Revie, Akartunalı, Day, Boulougouris [41]’Quandt, Beinke, Ait-Alla, Freitag [71]’ Tekle Muhabie, Rigo, Cepeda, de Almeida D’Agosto, Caprace [72]
Process-time variability	Irawan, Akbari, Jones, Menachof [22]’Sarker, Faiz [34]’Irawan, Jones, Ouelhadj [38]	Barlow, Tezcaner Öztürk, Revie, Akartunalı, Day, Boulougouris [41]’Leontaris, Morales-Nápoles, Wolfert [73]’Santos, Teixeira, Soares [74]’Guo, Chen, Chiu [75]’Castro-Santos, Filgueira-Vizoso, Lamas-Galdo, Carral-Couce [76]	Cheng, Wu, Wu, Ndure [33]

Boulougouris [41] determines the vessel capacity based on the number of modules it can carry of certain turbines.

2) Input variation, e.g., flow of materials, information, tooling, equipment, and resources; Vis, Ursavas [40]’ Tekle Muhabie, Rigo, Cepeda, de Almeida D’Agosto, Caprace [72] presented different installation compositions based on the nacelle with hub and blade configuration from the onshore; bunny ear, rotor star, and separate parts. The tower either being partially or fully assembled, Sarker, Faiz [34] followed the same principles, but also expands on batch size, with a fixed number of modules and lifts.
3) Location variation, e.g., the workstations, harbor, and remote assembly locations; the onshore on-site assembly is known as pre-assembly [22,38,81] prepares modular parts. These are then moved to the final assembly at remote locations offshore [18,41,46], where crews move through the locations which are also relevant for offshore maintenance. Dalgic, Lazakis, Turan, Judah [50] describe how the water depth defines the limitations of the offshore location for both foundations and installation vessel types. Stålhane, Halvorsen-Weare, Nonås, Pantuso [57] instead focused on distance from base (onshore) to the offshore location and how this would influence the resource selection. This indicates that the location affects the selection, but despite technical limitations or distance, the locations are not being further investigated.

3. Methodology

The primary focus of this research is on offshore wind project management and decision making, secondly how the overall variability behaves during execution at the onshore and offshore assembly location in offshore wind projects. This research project followed a deductive qualitative study approach [82,83]. Extensive literature reviews were conducted focusing on, but not limited to, these keywords: 1) offshore wind, project management, or planning, addressing on-site assembly both “locally” and “remotely”, and 2) on variability within: production, construction, and projects. The literature search was carried out using ScienceDirect, Scopus, and Google Scholar.

To understand the subject in-depth, six cases were identified for comparison, in alignment with the holistic multiple-case study [84]. The archival data from the six cases was obtained in form of historical progress reports including both the onshore and offshore locations. The case data was examined using statistical analysis, such as the Kolmogorov-Smirnov test, to determine the distribution and frequency of flow and process-time data points.

3.1. Case selection

Six cases were selected from diverse contexts inspired by McCutcheon, Meredith [85] in terms of (1) turbine features (hub height, rotor dimensions, foundation (excluding floating foundations) and tower interface) providing natural variation in products, (2) size of the projects (number of turbines) and contract features (vessel type, contract type, equipment, and resources) providing variation in material and information flow, and (3) location of the projects (country, harbor location, water depth, and distance from the site and shore) providing variation in location. These cases were selected so that each of them either predicts similar results or predicts contrasting results but for anticipated reasons [84,86]. Case study data from these diverse cases also provide more opportunities for checking alternative explanations and comparisons. The case projects are from the year 2016–2019 and are located in the UK and western Europe.

3.2. Case data

Table 2 shows the features of the six selected cases for our study (case A to case F). These cases represent an offshore project executed by a single producer for multiple developers from Europe. This included both onshore processes where parts of the turbine were pre-assembled, offshore where the turbine is installed and commissioned. Various features of the six cases are presented in Table 2.

3.3. Data analysis

The data-points are created by the occurrence of flow variability or process-time variability. Each data set consists of historical project delays, first categorized by location: 1) "Onshore" relating to activities executed during pre-assembly, 2) "Offshore" relating to activities executed during both the installation and commissioning phase of the projects. The variabilities were categorized as follows: 1) "Flow" was registered when work was hindered or paused from starting, 2) "Process-time" was registered when work had started but did not complete on time. Cases C and D had low onshore data registrations, therefore onshore data comparison will consist of four cases (A, B, E, and F) and offshore data comparisons will consist of all six cases.

To enable statistical testing, the data is grouped into data-points consisting of 500 activities. The grouping is chronological, based on a date. The grouping of data is analogous to Lindhard, Wandahl [87], except the creation of data-points is made according to specific quantities rather than specific time intervals. The findings from the six cases are statistically compared to identify differences in frequencies between both the onshore and offshore phase and between flow variability and process time variability. The process for the analysis: (1) determine mean and standard (Std.) deviation, (2) test for normality with the Kolmogorov-Smirnov test, (3) identify differences between variabilities with the Kruskal-Wallis test, (4) investigate differences in frequency between the variabilities with the Wilcoxon Signed Rank test, (5) investigate differences between location with the Mann-Whitney *U* test.

4. Results

As mentioned during the literature review, wind turbine project consists of different construction phases conducted at two very different work locations, onshore and offshore, respectively. Variability in flow and process-time has been registered in both phases. A total of 183,197 registrations have been made: 39,918 in the onshore phase and 143,279 in the offshore phase. The data enables the testing of each location and a comparison between locations and variability types. First, a normality test is conducted with the Kolmogorov-Smirnov test to identify what kind of statistics to apply. The test compares the sample to a normal distribution based on the sample mean and standard deviation. The Kolmogorov-Smirnov test can, while taking in mind the skewness and kurtosis values, be used to determine if a sample can be considered normally distributed or not. The test results from the Kolmogorov-Smirnov test are shown in Table 3.

According to the Kolmogorov-Smirnov test, neither the flow variability nor the process-time variability follows a normal distribution. Thus, the following analysis is based on non-parametric statistics.

First, a Kruskal-Wallis test is performed to identify if there are significant differences between the different construction cases. The Kruskal-Wallis test is used when testing for differences in several independent groups. The total variability is included to see if there are any tendencies at an overall level. The total variability is equal to the sum of the flow- and process-time variability. The test result is presented in Table 4.

Table 3
A Kolmogorov-Smirnov test, to test if the data is normally distributed.

Location	Variability	Skewness	Kurtosis	Kolmogorov-Smirnov Sig.
Onshore	Flow variability	2.768	11.927	.000
	Process-time variability	1.022	.954	.002
Offshore	Flow variability	.705	.305	.000
	Process-time variability	.632	.500	.001

Table 2
Data description of the followed cases.

	Case A	Case B	Case C	Case D	Case E	Case F
Installation start	2019	2016	2016	2016	2017	2018
Total number of turbines	102	67	42	67	56	42
Hub height	92 m	110 m	79,5 m	103 m	105 m	108 m
Rotor diameter	154 m	154 m	108 m	154 m	154 m	154 m
Contract	General contractor	General contractor	General contractor	General contractor	General contractor	General contractor
Contract schedule	Critical Path Method	Critical Path Method	Critical Path Method	Critical Path Method	Critical Path Method	Critical Path Method
Location	United Kingdom	United Kingdom	Netherlands	Germany	United Kingdom	Belgium
Pre-assembly port	Great Yarmouth	Hull	Amsterdam	Esbjerg, Denmark	Great Yarmouth	Oostende
Foundation	Jacket	Monopile	Monopile	Monopile	Monopile	Monopile
Distance to shore	45.2 km	35 km	0.5 km	95 km	27 km	34 km
Water depth	29–41 m	11–23 m	3–7 m	39–41 m	40–50 m	23–34 m
Installation vessel	Self-propelled jack-up vessel (DEME Sea Challenger)	Self-propelled jack-up vessel (A2SEA Installer)	Jack-up barge (Van Oord)	Self-propelled jack-up vessel (Fred. Olsen Brave Tern)	Self-propelled jack-up vessel (Blue Swire Pacific Osprey)	Self-propelled jack-up vessel (DEME Sea Installer)
Installation Composition	Separate parts (full tower, nacelle, 3 blades)	Separate parts (full tower, nacelle, 3 blades)	Full rotor star (2 tower pieces, nacelle, rotor)	Separate parts (full tower, nacelle, 3 blades)	Separate parts (full tower, nacelle, 3 blades)	Separate parts (full tower, nacelle, 3 blades)
Installation batch sizes	4	4	1	4	5	2
Commissioning vessel	Service operation vessel with a gangway	Service operation vessel with a gangway	Crew transfer vessel from shore	Service operation vessel with a gangway	Service operation vessel with a gangway	Crew transfer vessel from shore
Period Followed	52 weeks	44 weeks	21 weeks	82 weeks	42 weeks	43 weeks
Data registrations						
Onshore	11.816	–	359	855	15.676	11.212
Offshore	39.666	36.595	1.236	32.508	18.992	14.282
Total	51.482	36.595	1.595	33.363	34.668	25.494

Table 4
Kruskal-Wallis test for significant differences between construction cases.

Location	Variability	Test statistic	Degrees of Freedom	Sig.
Onshore	Flow variability	9.741	3	.021
	Process-time variability	8.176	3	.043
	Total variability	8.143	3	.043
Offshore	Flow variability	101.041	5	.000
	Process-time variability	49.798	5	.000
	Total variability	68.040	5	.000

The test results show that the distribution of variability in the followed cases is significantly different for both onshore variability and the variability in the offshore phase. The difference might be caused by a single case, thus further analysis is carried out to identify where the differences lay. First, the onshore flow variability is examined.

Table 5 reveals that despite the summed distribution being different between cases, there are no significant differences between each case. Moreover, the pairwise comparison reveals that the distribution of data in Case F has the weakest relationship. A Kruskal-Wallis test excluding Case F, confirms that Cases A, D, and E can be regarded as one distribution with a significance level for flow variability at 0.204, process time variability 0.542, and total variability at 0.338.

In Table 6 the offshore differences in distributions are examined case by case. Case C has been excluded due to limited data.

The pairwise comparison of cases reveals that none of the cases has a strong relationship when considering both flow variability, process time variability, and total variability. Cases A, C, F have relating flow and process variability, while Cases B and D have relating flow variability and Case B and E have relating process time variability. Therefore, in the following analysis, Cases A, B, C, D, E, and F are analyzed individually. Table 7 below contains some basic descriptive statistics.

The findings show that when scheduling in onshore construction, the expected number of delayed activities due to either flow or process time variability is around one third, Cases A, D, and E has a mean of 42.37, while Case F has a mean of 31.08. In the offshore phase, the lowest number of delayed activities are found in case E and is found to be varying between one third and two thirds. The best performing case is Case E with a mean value of 30.26% while the highest number of delayed activities are found in Case D and is found to be 59.38%.

When looking at flow variability, the mean value in the onshore phase is around 5% in Cases A, D, and E the mean is 5.06 and in Case F, the mean is 6.51. In the offshore phase, the mean is between 3.86 and 19.91.

Table 5
Differences in onshore variability. The significance level is adjusted for Type 1 error.

Flow variability	Case A	Case D	Case E	Case F
Case A	–	.935	1.000	.062
Case D			1.000	1.000
Case E				.350
Case F				–
Process time variability	**Case A**	**Case D**	**Case E**	**Case F**
Case A	–	.935	1.000	.062
Case D			1.000	1.000
Case E				.350
Case F				–
Total variability	**Case A**	**Case D**	**Case E**	**Case F**
Case A	–	.442	1.000	.091
Case D			.799	1.000
Case E				.779
Case F				–

Case B and C not included due to insignificant number of onshore registrations.

Table 6
Differences in offshore variability, adjusted for Type 1 error.

Flow variability	Case A	Case B	Case C	Case D	Case E	Case F
Case A	–	.000	–	.000	.011	1.000
Case B		–	–	1.000	.000	.000
Case C			–	1.000	.882	1.000
Case D				–	.000	.000
Case E					–	1.000
Case F						–
Process-time variability	**Case A**	**Case B**	**Case C**	**Case D**	**Case E**	**Case F**
Case A	–	.000	–	1.000	.001	1.000
Case B		–	–	.000	1.000	.000
Case C			–	1.000	1.000	.634
Case D				–	.010	1.000
Case E					–	.007
Case F						–
Total variability	**Case A**	**Case B**	**Case C**	**Case D**	**Case E**	**Case F**
Case A	–	.010	–	1.000	.000	.756
Case B		–	–	.001	.001	1.000
Case C			–	1.000	1.000	1.000
Case D				–	.000	.223
Case E					–	.002
Case F						–

Table 7
Mean and Std. deviation of the different cases.

Location	Case	Variability	Data points	Mean	Std. Deviation
Onshore	Case A, D, E	Flow variability	55	5.07	6.14
		Process-time variability	55	37.31	23.03
		Total variability	55	42.37	23.69
	Case F	Flow variability	22	6.51	3.37
		Process-time variability	22	24.57	8.29
		Total variability	22	31.08	8.28
Offshore	Case A	Flow variability	79	6.51	3.37
		Process-time variability	79	24.57	8.29
		Total variability	79	31.08	8.28
	Case B	Flow variability	73	19.91	6.19
		Process-time variability	73	26.40	9.03
		Total variability	73	46.31	10.45
	Case C	Flow variability	65	19.45	9.16
		Process-time variability	65	39.94	16.10
		Total variability	65	59.38	17.85
	Case D	Flow variability	37	3.86	5.73
		Process-time variability	37	26.39	9.90
		Total variability	37	30.26	11.40
	Case E	Flow variability	28	6.59	7.04
		Process-time variability	28	41.83	13.76
		Total variability	28	48.41	13.83
	Case F	Flow variability	55	5.07	6.14
		Process-time variability	55	37.31	23.03
		Total variability	55	42.37	23.69

Process time variability in the onshore phase is found to be between 24.57 and 37.31, while in the offshore phase it is found to be between 24.57 and 41.83.

To be sure that the difference between flow variability and process time variability is significant, a Wilcoxon Signed Rank test is performed. The Rank test compares and ranks the flow- and process-time variability of every data group based on frequency. Thus, the test shows if there are significant differences in frequencies between the two types of variability. The results of the Wilcoxon Signed-Rank test are presented in Table 8 below.

The test revealed that in all cases, process-time variability is significantly higher than flow variability. Moreover, the median frequency of occurrences of flow variability is found to be between 13.6% and 41.7%, lower than the frequency of process-time variability. This is excluding Case B, where the difference is significantly lower than any of the other cases.

To identify if there is a significant difference between the onshore and the offshore phase, a Mann-Whitney *U* test is performed. The Mann Whitney test is comparing the onshore phase to the offshore phase by calculating and comparing ranks, based on frequencies. The result is shown in Table 9 below.

The test revealed that there is a significant difference between variability in the onshore and offshore phase of wind turbine projects. It can be concluded that variability, in general, is significantly higher at the remote location offshore, where the difference of the medium frequency of both variabilities is between 8 and 19.2%.

5. Discussion

An operational perspective recognizes how offshore and onshore wind projects combine both production by (multiple similar products) and construction (project-based on-site assembly). Both Lerche, Neve, Wandahl, Gross [88] from an offshore wind perspective and O'Connor, O'Brien, Jin [89] from a general construction perspective confirm this notion, arguing it to be modular construction. Despite the installation compositions can be different [34,40,44], wind turbine construction follows a homogenous sequential modular assembly strategy [90]. Which is indifferent from floating wind assembly strategy [43,44]. What is important to recognize besides the modular strategy, is as Enevoldsen, Xydis [80] argued, the major difference over 35 years is only the size of the turbine components. Due to this, it can be argued that the findings are generalizable from an operational perspective, as the cases follow similar modular assembly processes.

From an assembly perspective, it is important to understand that wind turbine projects are highly repetitive. As each turbine resembles a predetermined number of similar activities, which is confirmed from various planning perspectives [15,17,18,41,63,69]. Hence utilization of the project features as variations could be perceived to be a limiting factor. But the high number of repetitive activities spread across a few cases would still make the results generalizable for the case variations selected.

The tests revealed that process-time variability is significantly higher than flow variability at both onshore and offshore. This supports Sovacool, Enevoldsen, Koch, Barthelmie [91] argument about wind project performance, that it is not about what is being managed, but how it is managed. As the process-time variabilities dominantly are within the project manager or project teams' control, it could be argued that the flow variabilities at the remote locations are related to the weather (wind or wave restrictions), this has though not been further investigated within this research project. Undeniably, the variations are caused for process complexity and it would require future investigation to grasp their interrelation or correlations. It is recognized that based on the number of cases, a generalizable picture of how the process variations act does not exist in detail, this would require further research. To further expand on the results presented here and their relevance for practitioners and academics, the same order as the results in our comparisons should be followed.

Table 9
Test results from the Mann-Whitney *U* test.

Case	Variability	Rank	Onshore vs. Offshore		95% confidence interval	
			Mann-Whitney U	Sig.	Lower	Upper
All	Flow variability	118/198	15.808	.000	−10.8	−5.2
	Process-time variability	147/190	13.572	.001	−12.2	−3.0
	Total variability	115/199	16.044	.000	−21.4	−11.4

Case B and C were not included due to the insignificant number of onshore registrations.

5.1. Impact of onshore variability

For the onshore variability, it could be argued that the natural variations e.g., hub height and rotor diameter would be influential. Furthermore, Case C did not have enough data points for its onshore assembly due to the difference in installation composition which would have been interesting to analyze. But those things aside, the hub height differentiated through all projects, and as did the foundation interface. This supports the argument that the "separate part" composition acts homogeneously from a variability distribution perspective. From a standard deviation standpoint, Case F reveals a better accuracy in comparison to Cases A, D, and E, which the reasoning for this has not been identified through the literature, however, a potential reason could relate to the "way things are being managed". The Case F batch size is significantly smaller than the other cases, making the ratio between work in progress and throughput more important when considering Little's law [2,92]. Seemingly, the batch size has a minor influence on the distribution of the variabilities onshore. Furthermore, Lerche, Neve, Ballard, Wandahl, Gross [18] elaborate on the difference of Case F in comparison to Cases D and E in particular, a different planning method was implemented here. And as the dominant variability is related to process-time, relying on system readiness, which the CPM is not known for [25,26]. These findings confirm the variability perspective which [22,33,34,38] base their predictive calculations upon. Whereas it also rejects the perception of the onshore assembly as a product dispatching station [41,71,72]. It is recognized that the different predictive models are utilized for different purposes, which to some extent determines the variability perspective.

Table 8
Comparison of differences between flow and process-time variability.

Variability	Location, Case	Positive differences	Negative differences	Ties	Sig.	95% Confidence interval	
						Lower Difference	Upper Difference
Flow vs. Process-time variability	Onshore, Case A, D, E	4	50	1	.000	−38.0	−24.5
Flow vs. Process-time variability	Onshore, Case F	0	22	0	.000	−22.1	−13.6
Flow vs. Process-time variability	Offshore, Case A	14	64	1	.000	−38.2	−23.1
Flow vs. Process-time variability	Offshore, Case B	21	52	0	.000	−9.1	−3.3
Flow vs. Process-time variability	Offshore, Case D	8	56	1	.000	−24.3	−14.5
Flow vs. Process-time variability	Offshore, Case E	1	36	0	.000	−26.5	−18.8
Flow vs. Process-time variability	Offshore, Case F	0	28	0	.000	−41.7	−27.8
Flow vs. Process-time variability	Overall	49	309	3	.000	−24.0	−19.2

5.2. Impact of offshore variability

The differences in case variations and variabilities are interesting, for instance, the water depth, distance to shore, and foundation types could be considered to have less impact on the variability distribution. This could be argued as Table 6 revealed similar variability distributions for B, D, or A, C, F despite their natural variation differences, especially the distance to shore and water depth Markard, Petersen [93] sees as project restrictions. The findings here indicate these factors to be less of a restriction from a project productivity and variability perspective. Also, that the cases have different standard deviations indicate that fixed value cannot be used alone e.g., Tekle Muhabie, Rigo, Cepeda, de Almeida D'Agosto, Caprace [72]. Caron, Ruggeri, Pierini [31] on the other hand did not consider the offshore location as a reason for an increase in variability or risk, nor did the offshore installation or operation articles with a "flow" oriented view from Table 1 consider the distribution between flow and process-time variability. Leontaris, Morales-Nápoles, Wolfert [73] utilizing a Bayesian model, revealed how the offshore installation process-time could relate to the chosen vessel, though this has not been further investigated here. Thought, it is recognized that different vessels were present in the various cases and as the process-time variability for Cases B and E are similar despite the vessels are different.

Interestingly, Cases B and D have considerable similar flow variability, where Case E is significantly lower, and without distinct variation differences, it is hard to determine plausible reasons for this. But as Cases E and A are assembled at the same onshore location, their differences might again relate to arguing that it is not what, but how it is being managed. It could be argued that installation and commissioning should be segregated to understand the impact of vessels, compositions, and batch sizes. Lacal-Arántegui, Yusta, Domínguez-Navarro [24] for instance found a downward trend for installation times on both turbines and foundations without dividing these either.

5.3. Comparing onshore to offshore

From a modular assembly perspective strategy, Peltokorpi, Olivieri, Granja, Seppänen [90] would argue that the modular assembly processes are considerably similar. Our results talk into this discussion, showing that onshore activities are more likely to commence and not held from starting as its offshore counterparts, case B and C in particular. Which emphasizes that assembly location is an important variable for completion. Also supporting Koskela [26] and Sacks [79] who argued that location flows are important for good productivity in construction. Not only was it identified how the distribution of the variabilities onshore and offshore differ. The total variation for offshore also exceeds the onshore locations, supporting Sovacool, Enevoldsen, Koch, Barthelmie [91] who argued that the offshore assembly location and vessels utilized here are the main differences between onshore and offshore wind projects.

Which could have been anticipated, this would lead to a good performance at the remote location. Goldratt [94] would argue the onshore location to be a feeder buffer for the offshore location from a critical chain perspective. As the flow variability is considerably lower could be argued to be related to buffering at both on-site assembly locations. But our results do not support that there is a performance connection. The findings here presented, do to some extent, reject that good performance at the onshore locations has a positive effect on its connected remote-location. It could further be argued that a deeper understanding of the variations would be required to support this argument.

5.4. Impact on current project management

The law of variability by Hopp, Spearman [2] states that *"increasing variability always degrades productivity of a production system"*. Interestingly Sovacool, Enevoldsen, Koch, Barthelmie [91] revealed that onshore wind projects have a mean cost overrun at 0.77% points, which was 8.83% points less than offshore wind projects cost overrun. These differences in cost overruns support the project performance differences from a cost perspective. The relation to the findings would be seen with the increase in variability at the offshore location. Kerkhove, Vanhoucke [20] introduced another cost perspective, relying on the assumption that durations would be the shortest possible. The process-time variability presented here would affect this assumption negatively and thereby impact the project cost. Hopp, Spearman [2] argued that variability can be controlled by buffering: capacity, inventory, or time. Goldratt [94] supports this and argued that a feeder buffer protects the critical activities in the projects, but also adds resources, further, the results revealed that it is also necessary to have a focus on the process-time variability. From a risk perspective, Steyn [95] sees this as an identified risk. Tommelein, Riley [37] argued the risk being related to the parade of trades, which again relates to the managing of resources and their flow through the locations. Adding to this, Ballard [96]; Koskela [26]' Lindhard [97] would argue that variations and understanding these is what would reduce the variability and increase project productivity.

Contributing to the theoretical discussion, Koskela, Howell [25]' Koskela [26] argued that dispatching of activities and lack of system readiness due to utilizing CPM is the reason for increases in project variability. What if the variability means are not affected by the planning, but instead this affects the certainties based on the standard deviations as seen in Case F, as Lerche, Neve, Ballard, Wandahl, Gross [18] documented the Last Planner System as an alternative to the current planning methods. Others again would argue that risk management applied to the critical path method would reduce the variability means and their standard deviations. Bayesian has, for example, networks being utilized to predict project outcomes, e.g., Caron, Ruggeri, Pierini [31] utilized this method and had external explicit knowledge for verification of the results in offshore oil and gas projects. But despite offshore wind and oil and gas projects operating at two different locations, this was not included in the calculations. Cheng, Wu, Wu, Ndure [33] further were inconsiderate of the process-time risk. Other risk predictive methods could positively benefit from the findings presented here. Firstly, these findings reject the thought that assembly locations act identically, and that good performance is automatically transferred. Secondly, it pushes the offshore wind projects' management understanding about process-time variability and its importance.

6. Conclusion

The empirical knowledge within the renewable energy domain of the offshore wind project variability is still limited as past planning and prediction methods have so far focused on the flow variabilities for remote location assembly. The findings show that flow variability is important, but not dominant as the literature suggests. Previous scientific contributions have primarily been focusing on the offshore location; however, this study concludes that insight into the entire process is required to define the severity of planning parameters.

As offshore wind is highly repetitive it is interesting to find such irregularities in the offshore assembly variabilities. The results showed that focusing on flow variability alone would not be adequate for realistic project performance predictions. Stretching that a change of perspective would be required, encouraging practitioners and academics to focus on planning methods that consider activity preparation or readiness before start. This change of focus towards process-time variability could lead to increase in the productivity for offshore wind projects and thereby affect the overall durations and costs. The differentiating project features only supports this, as alternating conditions did not perform better or worse. As the results leans towards being generalizable, it emphasizes that a single strategy for preparing, installing and commissioning the offshore wind turbine modules is not suitable for future projects. Especially as the results show that there is no connection between onshore performance and offshore performance. Further research would be required to understand in-depth what features from the cases that affect variability and how.

Credit author statement

Jon Lerche: Writing – original draft, Writing – review & editing, Methodology, Data curation, Formal analysis, Conceptualization, Project lead. Peter Enevoldsen: Writing – original draft, Writing – review & editing, Methodology, Conceptualization. Hasse H. Neve: Writing – original draft, Writing – review & editing, Conceptualization. Søren Lindhard: Writing – original draft, Writing – review & editing, Data curation. Velaayudan Arumugam: Writing – original draft, Writing – review & editing, Data curation. Jochen Teizer: Writing – original draft, Writing – review & editing. Søren Wandahl: Writing – original draft, Writing – review & editing, Formal analysis.

Data availability statement

Data generated or analyzed during the study are available from the corresponding author by request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] R.W. Schmenner, M.L. Swink, On theory in operations management, J. Oper. Manag. 17 (1) (1998) 97–113.
[2] W.J. Hopp, M.L. Spearman, Factory Physics : Foundations of Manufacturing Management, 2. edition, Irwin/McGraw-Hill, New York, N.Y., 1996.
[3] A.H. Al-Momani, Construction delay: a quantitative analysis, Int. J. Proj. Manag. 18 (1) (2000) 51–59.
[4] S.M. Lindhard, F. Hamzeh, V.A. Gonzalez, S. Wandahl, L.F. Ussing, Impact of activity sequencing on reducing variability, J. Construct. Eng. Manag. 145 (3) (2019), 04019001.
[5] M. Arashpour, A. Heidarpour, A. Akbar Nezhad, Z. Hosseinifard, N. Chileshe, R. Hosseini, Performance-based control of variability and tolerance in off-site manufacture and assembly: optimization of penalty on poor production quality, Construct. Manag. Econ. 38 (6) (2020) 502–514.
[6] P. Dallasega, E. Marengo, A. Revolti, Strengths and shortcomings of methodologies for production planning and control of construction projects: a systematic literature review and future perspectives, Prod. Plann. Control (2020) 1–26.
[7] M.O. Sanni-Anibire, R. Mohamad Zin, S.O. Olatunji, Causes of delay in the global construction industry: a meta analytical review, Int. J. Construct. Manag. (2020) 1–13.
[8] H. Karami, A.O. Olatunji, Critical overrun causations in marine projects, Eng. Construct. Architect. Manag. 27 (7) (2020) 1579–1594.
[9] H. Neve, S. Wandahl, S. Lindhard, J. Teizer, J. Lerche, Determining the relationship between direct work and construction labor productivity in north America: four decades of insights, J. Construct. Eng. Manag. 146 (9) (2020), 04020110.
[10] A. Sartal, M. Rodríguez, X.H. Vázquez, From efficiency-driven to low-carbon operations management: implications for labor productivity, J. Oper. Manag. 66 (3) (2020) 310–325.
[11] F. Innella, M. Arashpour, Y. Bai, Lean methodologies and techniques for modular construction: chronological and critical review, J. Construct. Eng. Manag. 145 (12) (2019), 04019076.
[12] M. Liu, Improving labor productivity through production control, in: 16th Annual Conference of the International Group for Lean Construction, 2008.
[13] S. Ganesan, Construction productivity, Habitat Int. 8 (3) (1984) 29–42.
[14] R.W. Revans, Manufacturing productivity, Omega 11 (6) (1983) 523–535.
[15] J. Lerche, O. Seppänen, K.B. Pedersen, H. Neve, S. Wandahl, A. Gross, Why would location-based scheduling Be applicable for offshore wind turbine construction?, in: Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC); 2019/07/03, 2019 (Dublin, Ireland).
[16] J. Lerche, H. Neve, K.B. Pedersen, S. Wandahl, A. Gross, Why would location-based scheduling Be applicable for offshore oil and gas construction?, in: Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC); 2019/07/03, 2019 (Dublin, Ireland).
[17] J. Lerche, H. Neve, S. Wandahl, A. Gross, Continuous improvements at operator level, J. Eng. Proj. Prod. Manag. 10 (1) (2020) 64–70, https://doi.org/10.2478/jeppm-2020-0008.
[18] J. Lerche, H. Neve, G. Ballard, S. Wandahl, A. Gross, Application of Last Planner System to modular offshore wind construction, J. Construct. Eng. Manag. (2020) (In review).
[19] S. Leth, J. Lerche, H.H. Neve, S. Wandahl, Lessons for construction: delivering mega project on time through culture and hoshin kanri, in: Proc. 27th Annual Conference of the International Group for Lean Construction (IGLC); 2019/07/03, 2019 (Dublin, Ireland).
[20] L.P. Kerkhove, M. Vanhoucke, Optimised scheduling for weather sensitive offshore construction projects, Omega (United Kingdom) 66 (Part A) (2017) 58–78.
[21] T. Beinke, A. Ait Alla, M. Freitag, Resource sharing in the logistics of the offshore wind farm installation process based on a simulation study, Int. J. e-Navigation Maritime Eco. 7 (2017) 42–54.
[22] C.A. Irawan, N. Akbari, D.F. Jones, D. Menachof, A combined supply chain optimisation model for the installation phase of offshore wind projects, Int. J. Prod. Res. 56 (3) (2018) 1189–1207.
[23] P.D. Galloway, CPM scheduling - how industry views its use, Cost Eng. 48 (1) (2006) 24.
[24] R. Lacal-Arántegui, J.M. Yusta, J.A. Domínguez-Navarro, Offshore wind installation: analysing the evidence behind improvements in installation time, Renew. Sustain. Energy Rev. 92 (2018) 133–145.
[25] L. Koskela, G. Howell, The underlying theory of project management is obsolete, in: Proc., PMI Research Conf., Newtown Square, PA, 2002.
[26] Koskela L. An Exploration towards a Production Theory and its Application to Construction [Article]. VTT Publications: Technical Research Centre of Finland2000.
[27] M. Welisch, R. Poudineh, Auctions for allocation of offshore wind contracts for difference in the UK, Renew. Energy 147 (2020) 1266–1274.
[28] W. Shen, X. Chen, J. Qiu, et al., A comprehensive review of variable renewable energy levelized cost of electricity, Renew. Sustain. Energy Rev. 133 (2020) 110301.
[29] V.T. Luu, S.-Y. Kim, N.V. Tuan, S.O. Ogunlana, Quantifying schedule risk in construction projects using Bayesian belief networks, Int. J. Proj. Manag. 27 (1) (2009) 39–50.
[30] J.S. Nielsen, J.D. Sørensen, Methods for risk-based planning of O&M of wind turbines, Energies 7 (10) (2014) 6645–6664.
[31] F. Caron, F. Ruggeri, B. Pierini, A Bayesian approach to improving estimate to complete, Int. J. Proj. Manag. 34 (8) (2016) 1687–1702.
[32] S.A. Enshassi Mohammed, S. Walbridge, S. West Jeffrey, T. Haas Carl, Dynamic and proactive risk-based methodology for managing excessive geometric variability issues in modular construction projects using bayesian theory, J. Construct. Eng. Manag. 146 (2) (2020), 04019096.
[33] M.-Y. Cheng, Y.-F. Wu, Y.-W. Wu, S. Ndure, Fuzzy Bayesian schedule risk network for offshore wind turbine installation, Ocean Eng. 188 (2019) 106238.
[34] B.R. Sarker, T.I. Faiz, Minimizing transportation and installation costs for turbines in offshore wind farms, Renew. Energy 101 (2017) 667–679.
[35] S. Alkass, M. Mazerolle, F. Harris, Construction delay analysis techniques, Construct. Manag. Econ. 14 (5) (1996) 375–394.
[36] E. Goldratt, Theory of Constraints, Great North River Press, 1999.
[37] I.D. Tommelein, D.R. Riley, Parade game: impact of work flow variability on trade performance, J. Construct. Eng. Manag. 125 (5) (1999) 304.
[38] C.A. Irawan, D. Jones, D. Ouelhadj, Bi-objective optimisation model for installation scheduling in offshore wind farms, Comput. Oper. Res. 78 (2017) 393–407.
[39] E. Barlow, D. Tezcaner Öztürk, M. Revie, E. Boulougouris, A.H. Day, K. Akartunalı, Exploring the impact of innovative developments to the installation process for an offshore wind farm, Ocean Eng. 109 (Supplement C) (2015) 623–634.
[40] I.F.A. Vis, E. Ursavas, Assessment approaches to logistics for offshore wind energy installation, Sustain. Energy Technol. Assessments 14 (Supplement C) (2016) 80–91.
[41] E. Barlow, D. Tezcaner Öztürk, M. Revie, K. Akartunalı, A.H. Day, E. Boulougouris, A mixed-method optimisation and simulation framework for supporting logistical decisions during offshore wind farm installations, Eur. J. Oper. Res. 264 (3) (2018) 894–906.
[42] J.H. Bookbinder, L.A. Koch, Production planning for mixed assembly/arborescent systems, J. Oper. Manag. 9 (1) (1990) 7–23.
[43] N. Bento, M. Fontes, Emergence of floating offshore wind energy: Technology and industry, Renew. Sustain. Energy Rev. 99 (2019) 66–82.
[44] Z. Jiang, Installation of offshore wind turbines: a technical review, Renew. Sustain. Energy Rev. 139 (2021) 110576.
[45] B. Scholz-Reiter, J. Heger, M. Lütjen, A. Schweizer, A MILP for installation scheduling of offshore wind farms, Int. J. Math. Models Methods In Appl. Sci. 5 (2) (2010) 371–378.
[46] A.A. Alla, M. Quandt, M. Lütjen, Simulation-based aggregate installation planning of offshore wind farms, Int. J. Energy 7 (2) (2013) 23–30.
[47] E.E. Halvorsen-Weare, C. Gundegjerde, I.B. Halvorsen, L.M. Hvattum, L.M. Nonås, Vessel fleet analysis for maintenance operations at offshore wind farms, Energy Procedia 35 (2013) 167–176.
[48] I.B. Sperstad, E.E. Halvorsen-Weare, M. Hofmann, L.M. Nonås, M. Stålhane, M. Wu, A comparison of single- and multi-parameter wave criteria for accessing wind turbines in strategic maintenance and logistics models for offshore wind farms, Energy Procedia 53 (2014) 221–230.
[49] I.A. Dinwoodie, D. McMillan, Operational strategies for offshore wind turbines to mitigate failure rate uncertainty on operational costs and revenue, IET Renew. Power Gener. 8 (4) (2014) 359–366.
[50] Y. Dalgic, I. Lazakis, O. Turan, S. Judah, Investigation of optimum jack-up vessel chartering strategy for offshore wind farm O&M activities, Ocean Eng. 95 (Supplement C) (2015) 106–115.

[51] Y. Dalgic, I. Lazakis, I. Dinwoodie, D. McMillan, M. Revie, Advanced logistics planning for offshore wind farm operation and maintenance activities, Ocean Eng. 101 (2015) 211–226.

[52] M. Shafiee, Maintenance logistics organization for offshore wind energy: current progress and future perspectives, Renew. Energy 77 (1) (2015) 182–193.

[53] K.R. Petersen, E.S. Madsen, A. Bilberg, First Lean, then modularization: improving the maintenance of offshore wind turbines, Int. J. Energy Sect. Manag. 10 (2) (2016) 221–244.

[54] A. Gutierrez-Alcoba, E.M.T. Hendrix, G. Ortega, E.E. Halvorsen-Weare, D. Haugland, On offshore wind farm maintenance scheduling for decision support on vessel fleet composition, Eur. J. Oper. Res. 279 (1) (2019) 124–131.

[55] G. Leontaris, O. Morales-Nápoles, A. Dewan, A.R.M. Wolfert, Decision support for offshore asset construction using expert judgments for supply disruptions risk, Autom. ConStruct. 107 (2019) 102903.

[56] A.H. Schrotenboer, E. Ursavas, I.F.A. Vis, Mixed Integer Programming models for planning maintenance at offshore wind farms under uncertainty, Transport. Res. C Emerg. Technol. 112 (2020) 180–202.

[57] M. Stålhane, E.E. Halvorsen-Weare, L.M. Nonås, G. Pantuso, Optimizing vessel fleet size and mix to support maintenance operations at offshore wind farms, Eur. J. Oper. Res. 276 (2) (2019) 495–509.

[58] C. Stock-Williams, S.K. Swamy, Automated daily maintenance planning for offshore wind farms, Renew. Energy 133 (2019) 1393–1403.

[59] V.M. Catterson, D. McMillan, I. Dinwoodie, et al., An economic impact metric for evaluating wave height forecasters for offshore wind maintenance access, Wind Energy 19 (2) (2016) 199–212.

[60] T. Gintautas, J. Sørensen, Improved methodology of weather window prediction for offshore operations based on probabilities of operation failure, J. Mar. Sci. Eng. 5 (2) (2017) 20.

[61] J. Paterson, F. D'Amico, P.R. Thies, R.E. Kurt, G. Harrison, Offshore wind installation vessels – a comparative assessment for UK offshore rounds 1 and 2, Ocean Eng. 148 (2018) 637–649.

[62] J.W. Taylor, J. Jeon, Probabilistic forecasting of wave height for offshore wind turbine maintenance, Eur. J. Oper. Res. 267 (3) (2018) 877–890.

[63] E. Ursavas, A benders decomposition approach for solving the offshore wind farm installation planning at the North Sea, Eur. J. Oper. Res. 258 (2) (2017) 703–714.

[64] S. Backe, D. Haugland, Strategic Optimization of Offshore Wind Farm Installation. Computational Logistics, 2017, 2017// (Cham).

[65] N.T. Raknes, K. Ødeskaug, M. Stålhane, L.M. Hvattum, Scheduling of maintenance tasks and routing of a joint vessel fleet for multiple offshore wind farms, J. Mar. Sci. Eng. 5 (1) (2017).

[66] A. Kovács, G. Erdős, Z.J. Viharos, L. Monostori, A system for the detailed scheduling of wind farm maintenance, CIRP Annals 60 (1) (2011) 497–501.

[67] I. Dinwoodie, O.-E.V. Endrerud, M. Hofmann, R. Martin, I.B. Sperstad, Reference cases for verification of operation and maintenance simulation models for offshore wind farms, Wind Eng. 39 (1) (2015) 1–14.

[68] C.A. Irawan, D. Ouelhadj, D. Jones, M. Stålhane, I.B. Sperstad, Optimisation of maintenance routing and scheduling for offshore wind farms, Eur. J. Oper. Res. 256 (1) (2017) 76–89.

[69] Y.T. Muhabie, J.-D. Caprace, C. Petcu, P. Rigo, Improving the installation of offshore wind farms by the use of discrete event simulation, in: 5th World Maritime Technology Conference, 2015 (Providence, RI, USA).

[70] M. Stålhane, H. Vefsnmo, E.E. Halvorsen-Weare, L.M. Hvattum, L.M. Nonås, Vessel fleet optimization for maintenance operations at offshore wind farms under uncertainty, Energy Procedia 94 (2016) 357–366.

[71] M. Quandt, T. Beinke, A. Ait-Alla, M. Freitag, Simulation based investigation of the impact of information sharing on the offshore wind farm installation process, J. Renew. Energy 2017 (2017) 11.

[72] Y. Tekle Muhabie, P. Rigo, M. Cepeda, M. de Almeida D'Agosto, J.D. Caprace, A discrete-event simulation approach to evaluate the effect of stochastic parameters on offshore wind farms assembly strategies, Ocean Eng. 149 (2018) 279–290.

[73] G. Leontaris, O. Morales-Nápoles, A.R. Wolfert, Probabilistic Decision Support for Offshore Wind Operations, 2018.

[74] F.P. Santos, A.P. Teixeira, C.G. Soares, Maintenance planning of an offshore wind turbine using stochastic petri nets with predicates, J. Offshore Mech. Arctic Eng. 140 (2) (2018).

[75] S.-J. Guo, J.-H. Chen, C.-H. Chiu, Fuzzy duration forecast model for wind turbine construction project subject to the impact of wind uncertainty, Autom. ConStruct. 81 (2017) 401–410.

[76] L. Castro-Santos, A. Filgueira-Vizoso, I. Lamas-Galdo, L. Carral-Couce, Methodology to calculate the installation costs of offshore wind farms located in deep waters, J. Clean. Prod. 170 (2018) 1124–1135.

[77] S. Bertelsen, G. Henrich, L. Koskela, J. Rooke, Construction physics, in: 15th Annual Conference of the International Group for Lean Construction; 2007/07/18, East Lansing, Michigan, USA, 2007.

[78] S. Bertelsen, L. Koskela, G. Henrich, J. Rooke, Critical flow – towards a construction flow theory, in: 14th Annual Conference of the International Group for Lean Construction; 2006/01/01, 2006 (Santiago, Chile).

[79] R. Sacks, What constitutes good production flow in construction? Construct. Manag. Econ. 34 (9) (2016) 641–656.

[80] P. Enevoldsen, G. Xydis, Examining the trends of 35 years growth of key wind turbine components, Energy Sustain. Develop. 50 (2019) 18–26.

[81] C.A. Irawan, X. Song, D. Jones, N. Akbari, Layout optimisation for an installation port of an offshore wind farm, Eur. J. Oper. Res. 259 (1) (2017) 67–83.

[82] J.W. Creswell, in: Los Angeles (Ed.), Research Design : Qualitative, Quantitative, and Mixed Methods Approaches, fourth ed.international student edition, SAGE, Calif., 2014.

[83] B.B. Flynn, S. Sakakibara, R.G. Schroeder, K.A. Bates, E.J. Flynn, Empirical research methods in operations management, J. Oper. Manag. 9 (2) (1990) 250–284.

[84] R.K. Yin, Case Study Research : Design and Methods, fifth ed., SAGE, Los Angeles, 2014.

[85] D.M. McCutcheon, J.R. Meredith, Conducting case study research in operations management, J. Oper. Manag. 11 (3) (1993) 239–256.

[86] M. Gibbert, W. Ruigrok, B. Wicki, What passes as a rigorous case study? Strat. Manag. J. 29 (13) (2008) 1465–1474.

[87] S. Lindhard, S. Wandahl, Exploration of the reasons for delays in construction, Int. J. Construct. Manag. 14 (1) (2014) 36–44.

[88] J. Lerche, H. Neve, S. Wandahl, A. Gross, Categorization of the offshore wind production system, Int. J. Oper. Res. (2019).

[89] J.T. O'Connor, W.J. O'Brien, O.C. Jin, Standardization strategy for modular industrial plants, J. Construct. Eng. Manag. 141 (9) (2015), 04015026.

[90] A. Peltokorpi, H. Olivieri, A.D. Granja, O. Seppänen, Categorizing modularization strategies to achieve various objectives of building investments, Construct. Manag. Econ. 36 (1) (2018) 32–48.

[91] B.K. Sovacool, P. Enevoldsen, C. Koch, R.J. Barthelmie, Cost performance and risk in the construction of offshore and onshore wind farms, Wind Energy 20 (5) (2017) 891–908.

[92] J.D.C. Little, A proof for the queuing formula: $l= \lambda W$, Oper. Res. 9 (3) (1961) 383–387.

[93] J. Markard, R. Petersen, The offshore trend: structural changes in the wind power sector, Energy Pol. 37 (9) (2009) 3545–3556.

[94] E. Goldratt, Critical Chain, The North River, Great Barrington, MA, 1997.

[95] H. Steyn, Project management applications of the theory of constraints beyond critical chain scheduling, Int. J. Proj. Manag. 20 (1) (2002) 75–80.

[96] G. Ballard, Improving work flow reliability, in: 7th Annual Conference of the International Group for Lean Construction; 1999/07/26, 1999 (Berkeley, USA).

[97] S. Lindhard, Understanding the effect of variation in a production system, J. Construct. Eng. Manag. 140 (11) (2014).