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The impact of COVID -19 on offshore wind project productivity – A case study

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ABSTRACT

This study investigated productivity in an offshore wind project to understand the distribution of their value-adding and non-value-adding hours. A comprehensive literature review presented results on productivity in regular mega-projects, revealing a limited knowledge of offshore wind projects. From the first quarter of 2019 to the early second quarter of 2020, 62,447 realized activities, equaling 213,786 h, were sampled from a wind farm development project in the British sector of the North Sea. This data was then analyzed and presented through a descriptive statistic. The results showed a distribution of 21.21% value-adding (VA) and 50.09% non-value-adding (NVA) hours. With 20.9% of the total hours, the weather is the dominant cause of waiting time, followed by vessels and previous tasks. The findings further show the disruptions of the COVID-19 pandemic and its effects on productivity. It supports and expands on existing knowledge of causes for waiting time in offshore wind projects, ultimately providing the industry with an understanding of areas that need development to enhance productivity. The paper contributes to current knowledge by providing an understanding of productivity in offshore wind projects.

1. Introduction

The offshore wind market is a continuous and rapidly expanding industry. It reaches beyond the European market, into the Asian, North American, and lately investigating opportunities in the South American market [1–6]. With offshore wind projects considered project-based productions [7], it receives and assembles large modules, materials, and resources provided from international supply chains [8]. Despite wind projects being part of the renewable energy sector for more than 30 years [4,9] and in the construction industry equally as long [7], little is known about productivity during assembly. When considering productivity, it is measured at different levels; 1) National level (macro-level), 2) Project or production plant level, 3) Operator level. 1) When measuring productivity on the macro-level, the ratio between the output of earned value and input of labor hours is investigated. This is then captured in national databases, containing decades of data for labor productivity in both manufacturing [10–12] and construction [13], yet, offshore wind labor productivity is not included in either database. 2) Measuring productivity at the project or plant level requires opting to either investigate; the relation between goods or objects coming out of the process in relation to the materials and resources added to the process [14], or the relationship between planned and complete activities [15–17]. 3) On the operator level, there has been a tendency to utilize the work sampling method [13,18], providing a relationship between the value-adding (VA) and non-value-adding (NVA) activities within a given time period [19]. But neither of these methods have previously been applied to gain an understanding of offshore wind productivity. This has left offshore wind projects in a grey zone, as it is considered a maturing industry, but has limited quantifiable knowledge of its productivity elements (VA or NVA activities).

Abbreviations: Capital Expenditure, (CapEx); Critical Path Method, (CPM); Denmark, (DK); MegaWatt, (MW); Last Planner System, (LPS); Non-value adding, (NVA); Project week, (PW); Self-propelled jack-up vessel, (JU); Service operating vessel, (SOV); Transformation-Flow-Value, (TFV); Value-adding, (VA); United Kingdom, (UK).

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1.1. Offshore wind project performance

Productivity measures might not be known, nonetheless, performance measures based on the completed number of assets over a specified duration are known and utilized, either as; reported outcomes, various planning methods looking to predict, or optimize potential outcomes [20–22]. From a project cost performance perspective, Sovacool, Enevoldsen [20] found that offshore wind projects have a cost escalation with a mean of 9.6%, which is 7.9% points higher than the mean cost escalation of onshore wind projects. The average time overrun of 45% from offshore wind projects has also been reported. Even more interesting is that Lacal-Arántegui, Yusta [23] presented how the offshore performance had improved in the same period, but mainly compared to days per installed MegaWatt (MW). Both Sovacool, Enevoldsen [20] and Lacal-Arántegui, Yusta [23] argued that it is not about what is being managed but how it is being managed.

While investigating the productivity of an offshore wind project, the global pandemic COVID-19 hit Europe in early 2020 [24], disrupting societies [25], energy sectors [26,27], supply chains [28,29], and mobility in general [30]. It also opened a unique opportunity to investigate firsthand how a disaster can disrupt a mega project's productivity and its supply chain, as the construction phase continued similar to hospitals [31], without home-office, or other flexible alternatives [32,33]. When facing undesired or disruptive events, Ye, Jiao [34] outlined that extremely short response times, complex demand assessment, challenged resource mobility, coordination issues, further inflicting budget, and resource limitations are likely to occur. It further stresses the importance of knowing the factors which affect your productivity [35], paving the objective of this research.

This study set out to describe and measure productivity at the project level by analyzing the historical progress data. To meet the objective, two units of analysis were developed on the basis of the literature review, data clustering, and qualitative verification from industry experts. The case inputs of productive and non-productive activities (including COVID-19 registrations) were categorized through data clustering, statistically analyzed, and presented as descriptive statistics. The first unit of analysis provided knowledge of the productivity, while the second unit of analysis expanded on non-productive hours, providing an understanding of the impact of COVID-19, along with other sources of delay. Through discussion and conclusion, the operations and project management implications of the findings are made clear.

This research contributes to the body knowledge by;

A. providing a model for analyzing non-value-adding activities within the offshore wind domain or similar contexts, and
B. the results provide an in-depth understanding of productivity in modular wind construction projects.

2. Productivity in operations management

Productivity, the relationship between inputs and outputs, is a mature topic [14] within the operation management domain. Koskela [36] contributed to this thinking by adding the conceptual understanding of what defines a production flow and further described productivity as a relationship between value-adding and non-value-adding activities. Faridi and El-Sayegh [37], Iyer, Chaphalkar [38], Kaming, Olomolaiye [39], Semple, Hartman [40] all found that productivity was the cause of delay in various project types. The understanding in this study follows Koskela [36], Sanni-Anibire, Mohamad Zin [41], who find productivity to be the result of ready and prepared activities. In addition to this, Hopp and Spearman [14], Neve, Wandahl [18], Ohno [42], Ballesteros-Pérez, Sanz-Ablanedo [43], Karami and Olatunji [44], Pall, Bridge [45] argued that when eliminating unnecessary activities (variability, delaying factors, and non-value adding activities, etc.), project or operations productivity would increase.

2.1. Productivity in offshore wind projects

In the planning perspective of an offshore wind project, productivity is seen in relation to activity or overall project durations. The dominant planning methods used in offshore projects are activity-based approaches following fixed sets of parameters, seeking to optimize durations by applying the critical path method (CPM) and models of either deterministic or stochastic character [22,46]. These methods are then used to solve logistic problems [47,48], optimizing the utilization of the resources (manning, equipment and vessels) while predicting weather windows. Irawan, Akbari [49] added to school of thought by expanding the knowledge of the inventory stocks of the larger modules. The parameters of the weather windows (wave heights and wind speeds) are also the dominant parameter for the models intending to solve installation problems and reduce the overall duration [47,50–56]. Besides the weather, these planning models also utilized the following parameters: components, equipment, resources, information, and safety, although, mainly considering them as binary conditions either present or not. Despite the number of models available, Lacal-Arántegui, Yusta [23] still emphasized that the current planning methods might not be adequate for future wind turbine projects. This study sees construction planning methods such as the last planner system (LPS) [15], Takt [57,58], or location-based management [59,60] as alternatives to the CPM. Especially LPS, which categorizes delaying factors as preconditions. Lerche, Neve [61] supported this, by implementing LPS and consequently reported an increase in productivity compared to the optimized CPM schedule. Nevertheless, limited knowledge exists about the causes of decreased productivity in offshore wind projects.

2.2. Model for analyzing productivity

A unit of analysis was developed to understand productivity in the offshore wind project context. Table 1 presents this unit of analysis, distributing data points with time weight among value-adding (work) and non-value-adding activities (other categories). The hours are not differentiated between trades - Neve, Wandahl [18] found that productivity is not trade-dependent. The table categories were inspired by

Table 1
Unit of analysis for activity categories.

Categories	Description
Break	Time spent on breaks [18] - indifferent to this being lunch, stops, or other activities reported as breaks.
Inspection	Time spent on inspecting the product assembled.
Meeting (Talking)	Olomolaiye, Wahab [63] described taking instructions as part of their data sampling, where Wandahl and Skovbogaard [64]. identified the same category without distinctions between private and professionals' talk. This research categorized it as – "Time spent on meetings internally or externally, toolbox talks, planning, or briefings (safety, work, technical or other)".
Preparation	Gong, Borcherding [62] considered preparation a part of this work, both Neve, Wandahl [18], Wandahl and Skovbogaard [64]. segregated preparation from the work category. This research followed a similar approach. This category reports – "Time spent on activities which include preparing materials, equipment, or tools".
Rework	This category reflects the "time spent on work rectifying quality issues, defects, snagging, or punch list items".
Transport/ travel	Olomolaiye, Wahab [63] defined transport as when materials were moved, whereas travel was emptyhanded. This research used it for "time spent on moving personnel, materials, equipment, tools by sailing, driving, or manual handling".
Waiting	This research followed the description of waiting by Abdel-Razek, Abd Elshakour M [65] as "Time reported on waiting for equipment, machinery, materials, weather, or other reasons".
Work	This category consists of the "transformations (activities that add or increase the product's value) or time spent processing materials, assembling processes, or operating assembly equipment".

Neve, Wandahl [18] and Gong, Borcherding [62].

2.3. Non-value adding activities affecting productivity

Through time, operational planning has responded to events of uncertainty - including crisis or disaster-during its everyday operations. These uncertainties are parameters of different characteristics or wording (e.g., uncertainty, emergencies, undesired events, variability, delays, or variations). All negatively affect durations and productivity from an operational, project, or planning perspective [66]. In CPM, the response to uncertainty is made through risk analysis and time or resource buffering, protecting the scheduled durations [67,68]. When managing risk in supply chains, the focus is on preserving the material or resource availability despite demand changes [69]. Offshore wind projects have done so through sourcing from local providers [70] and/or international providers [8,71], which is indifferent to managing a permanent production facility or a temporary project-based production. Koch [21] added to this by arguing that productivity would be impacted by weather, product technology, site features, or processes. Analyzing supply chain processes, Stauffer, Pedraza-Martinez [72] argued that it is vital to ensure resource availability and mobility in response to these times. Similar to van der Laan, van Dalen [73]'s focus on protecting the logistics and demand volatility with safety stocks, following predefined parameters aligned between every day and crisis operations. Das, Annand [74] added how transparency and information flow throughout the supply chain would enable control of the situation. In marine projects, Karami and Olatunji [44] mentioned how knowing the reasons for delay allows decision-makers to address productivity issues. Nonetheless, none of them addressed in detail what causes low productivity in offshore wind.

2.4. Model for analyzing non-value adding activities

The second unit of analysis expands the knowledge of the non-value-adding activities and, in particular, the delaying factors causing waiting time. As a unit of analysis was not compatible with the delay factors in the data set, one was developed through triangulation of project delay literature, data clustering, and qualitative analysis made in collaboration with industry experts. Comparable to Murphy, Schleifer [75] developed a taxonomy for energy systems, or Braglia, Dallasega [76] construction supply chains. Table 2 presents the delaying factors.

Table 2
Unit of analysis expanding waiting time.

Delay factor	Description
Components & Parts	Components being the modules, parts are all the minor assembly materials. Reported as a delay when lacking, inconsistent delivery, damaged or has other issues with the quality [65,77,78].
Equipment & Tools	The equipment is related to machinery, cranes, or onsite transport, where tools are hand-carried. It becomes a delay for similar reasons as components [79]. Karami and Olatunji [44] explored how mechanical stoppage or operators could contribute to this category for marine projects.
Information & Documentation	The information is reported when diagrams, drawings, instructions, or other documentation is late, missing, inadequate, or incomplete for the teams [80,81].
Location	The location or workspace is not accessible for various reasons, e.g., permits when offshore [82,83]. Offshore, it is also associated with foundations not available. Or related to space where teams work being unavailable for reasons such as other teams using the area [41].
Manning & Competence	Outlined how the capacity of workers, availability of resources, and labor can be sources for delays equally to the other categories if missing, not ready, or craftmanship of low quality. Underqualified would be categorized as a lack of competence.
Planning & Permit	Inadequate planning or information between management and the teams [37]. Further, it could also be related to poor coordination or commitment among actors [79,84].
Previous task	Tasks handed over incomplete, the time spent rectifying this or waiting for others to do so [85].
Safety	When the working conditions are unsafe, safety is reported, including both incidents and accidents [85].
Unexpected conditions (COVID-19)	This factor does not exist consistently throughout the dataset, as it was only present by the end of the case study. Disaster event registrations are yet unseen. Yet they would come by Chan and Kumaraswamy [86], Mishmish and El-Sayegh [87], Odeh and Battaineh [88] be classified as unforeseen events, or by Mukhtar, Khoiry Muhamad [89] force majeure.
Unspecified	This category contains those data points which caused waiting time but were not further classified.
Vessel	This includes all delays related to vessels used on-site to transport material or resources.
Weather	Ballesteros-Pérez, Sanz-Ablanedo [43], Ballesteros-Pérez, del Campo-Hitschfeld Maria [90], Ballesteros-Pérez, Rojas-Céspedes [91] investigated the impact on construction in general, the weather relates to both wave and wind as seen by Karami and Olatunji [44], Ruqaishi and Bashir [92]. It also includes lightning, thunderstorm, and fog.

3. Method and materials

The method section first introduces the units of analysis, then the case description, and last, the procedure for the statistical analysis. With offset in Voss, Tsikriktsis [93]'s understanding of exploration, this research project focus on value-adding (VA) and non-value-adding (NVA) activities in modular wind turbine construction.

3.1. Research framework

This research follows a framework as illustrated in Fig. 1 inspired by Yin [94], using a single case study approach with multiple units of analysis. Fig. 1 shows how the problem initiated the case study, leading to the case selection and literature review. This is also how the internal validity was developed [95]. The case was selected based on its project features (Table 3), data detail level, and total duration. The data collection was done by analyzing project progress reports. The data gathering and the developed units of analysis ensured the construct validity. The units of analysis ensure replicability of the study within the context, allowing for later quantifiability [96]. The external validity was built through different phases; a) comparison to existing literature, b) the dialogue with industry experts, and c) the discussion [97].

3.1.1. Developing the units of analysis

Developing the two units of analysis followed Koskela's [36] conceptual understanding of production systems. The flow view associated with the transformation flow value (TFV) theory of production is outlined below:

1. Conceptualization of production flow: flow of material, composed of transformation, inspection, moving, and waiting.
2. Main principle: elimination of waste (interpretation: unnecessary activity, movement, or waiting).
3. Methods and practices: continuous flow, pull, production control, continuous improvement.
4. Practical application: taking care that what is unnecessary is done as little as possible.
5. Suggested name for practical application of the view: flow management.

Step 1) The first unit of analysis was developed through the literature review and data clustering [98] VA and NVA activities, as shown in Fig. 1. Table 1 is the outcome of this, defining the activity categories

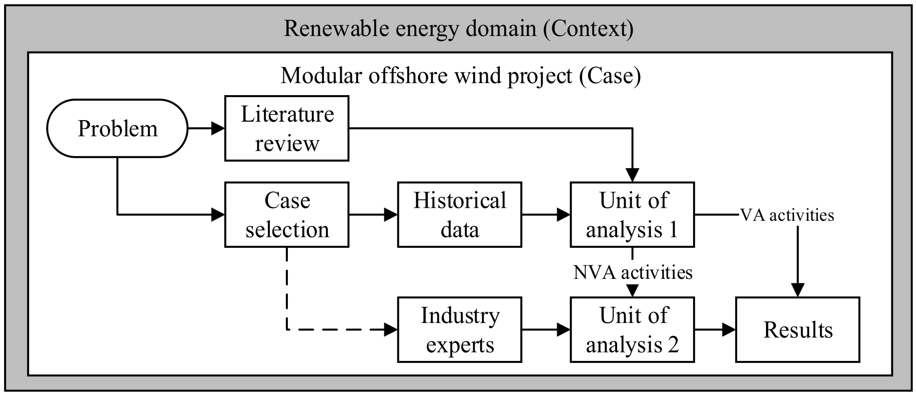


Fig. 1. Research framework.

based on different sampling methods. Step 2) The second unit of analysis was developed through data clustering [98] the reasons for NVA activities produced through the first analysis. Triangulation was used to verify the NVA by engaging a team of industry experts (a site manager, two supervisors, a mechanical- and an electrical-competent technician) from the case (dotted line in Fig. 1). The outcome is the clusters shown in Table 2. Step 3,4, and 5 are not considered further in this study.

3.1.2. Selected case

The case project description in Table 3 is organized by conditions providing an overview of the case in relation to relevant literature.

3.2. Case data

The primary data sources were from observations, interviews, and field notes. Where Neve, Wandahl [18], Gong, Borcherding [62], Olomolaiye, Wahab [63], Handa and Abdalla [107], Al-Ghamdi [108] utilized work sampling to collect both value-adding and non-value adding activities, this research followed Liu, Ballard [16], Abdel-Razek, Abd Elshakour M [65]'s method, focusing on labor productivity. It did not use the construction Percent-Plan-Complete (PPC) as a productivity measure [15,61,109,110]. The secondary data sources came from historical data such as progress reports and hour registrations.

3.2.1. Data analysis

The dataset consists of 62,447 documented activities containing information such as when the activities occurred, their duration, and type of activity. Activities with missing data on date and time were omitted from the dataset before conducting any statistical analysis. Predominantly, these activities pertain to breaks, lunch/dinner, daily briefings, and traveling. Additional data wrangling was needed to deal with inconsistent use of whitespace, capitalization, and singular versus plural form. Activities with a duration of zero were also omitted. The process left 54,144 activities for analysis. The activities' duration adds up to 213,786 h, 17 min, and 24 s. To put this statistic into perspective, the project would require 24 years, 147 days, 18 h, 17 min, and 24 s for a single unit of human resources. Out of the 54,144 activities, 39,631 of the activities (73.20%) are categorized as offshore. Analogously, 11,814 of the activities (21.82%) are onshore. The remaining 2699 (4.98%) activities are not classified.

Fig. 2 shows the activity durations' statistical distribution, proxied by a histogram and an Epanechnikov kernel density plot (bandwidth of 0.2087). On average, an activity exhibited a duration of 3.95 h. The mode, however, is 5.5 h. The shortest activity - ignoring activities with a recording duration of zero, was 0.02 h or 1 min and 20 s. The activity with the longest duration, on the other hand, lasted for 17 h.

4. Results

The results section is organized in accordance with the units of analysis.

4.1. Understanding productivity

The results from the first unit of analysis are presented in section 4.1.1, 4.1.2, and 4.1.3.

4.1.1. Distribution between value-adding and non-value-adding activities

The 54,144 activities can be assigned to eight different categories following the unit of analysis: inspection, meeting, preparation, rework, training, transport, waiting, and work. Fig. 3 shows the number of activities corresponding to each category and the aggregate time spent on each work category. As shown in Fig. 3, the three major components are waiting, work and preparation. The total project time was about 213,786 h. A total of 107,081 h were spent on waiting, i.e., 50.09% of the project time consisted of waiting. 47,826 (22.37%) and 45,339 (21.21%) hours were dedicated to preparation and work, respectively. Hence, productive time (preparation and work) contributed less to the total project time than unproductive time (waiting). Time spent on inspection, meetings, rework, training, and transport amount to 12,840 h and 6.33% with respect to all activities.

4.1.2. Distribution of hours

Additional insight into the behavior of the different work categories can be obtained by inspecting the statistical distribution of the conditional activity durations – see Fig. 4. As gleaned from Fig. 4, subfigure (b) - meeting, its average duration ranges from 1.04 h to 5.47 h subfigure (e) - training. On average, waiting activity - subfigure (g), had a duration of 4.58 h with a standard deviation of 1.86 h. Work activities - subfigure (h), on the other hand, had an average duration of 3.24 h with a standard deviation of 1.81 h. Subfigure (b) shows an outlier of 6-h meetings, which was traced back to project introductions, where the less than 30 min meetings were related to the daily beginning and end of shifts. Subfigure (f) shows that transport had a mean of 2.53 h with a standard deviation of 2.85 h, indicating that shorter trips with vessels were conducted. The use of a service operating vessel (SOV) supported this as it was positioned in the wind farm field close to the assembly locations.

4.1.3. Productivity measure over time

Fig. 5 depicts the percentage of time spent on preparation, work, and waiting for the sum of these three work categories. The y-axis shows the distribution in the percentage of the main productive and non-productive activities performed throughout the project weeks on the x-axis. Notably, preparation as the dominating activity until project week (PW) 10 can be explained for various reasons. It was a way of protecting the expensive vessel hours through time buffering as the

Table 3
Case description.

Conditions	Description
Duration	The case study was 60 calendar weeks conducted from quarter one (Q1) in 2019 and finalized by the beginning of quarter two (Q2) of 2020, at the beginning of the COVID-19 pandemic in Europe [24].
Country	The selected case was being developed in the United Kingdom (UK), which is considered part of a mature offshore wind market in Europe [5,99]. The differences in legislation or country-specific requirements or their impact on construction and operations are yet to be explored and were not pursued further.
Total number of turbines and power output	The case consists of 102 wind turbines with a total of 702 MW. Enevoldsen and Xydis [9] described the significant differences in turbine dimensions and power output in the last 35 years, especially the blade lengths (75 m here) and tower heights (95 m here). Are expected to impact both the installation compositions and vessels in the future.
Planning method	The contractual planning was a critical path method similar to what Irawan, Jones [54], Barlow, Tezcaner Öztürk [55] presented, as reported in the Oracle software package Primavera.
Capital Expenditure (CapEx)	The CapEx for the case is 2600 million British Pounds. Bosch, Staffell [100] related this to the development, manufacturing, and construction of wind farms. Sovacool, Enevoldsen [20] reported that the main difference in cost drivers between onshore and offshore wind projects lies with the offshore vessels.
Supply chain	The case followed a similar supply chain structure described by Poulsen and Lema [8], tower modules coming from Spain, Denmark (DK), and Vietnam. Nacelles were from Germany and DK, while blades were from UK and DK.
Resource hubs	The case organization used local (UK) and international resource hubs (including European countries as Denmark, Germany, and Poland) for the assembly activities.
Onshore assembly port	For this case, the port of assembly is the port of Great Yarmouth in the UK, following a layout similar to what Irawan, Song [101] described - a European port already made ready for receiving turbine components for assembly before being shipped offshore with the installation vessels. Lerche, Neve [61] explained these processes in depth while applying an alternative planning method.
Offshore assembly location (distance to shore, foundation type, and water depth)	Since the early 2000s offshore wind has consistently moved further away from shore [4], Ursavas [52] showed how foundation types alternate depending on the water depth for the particular area. Luo-Theilen and Rung [102], and Alla, Quandt [51] revealed how similar vessels are used to install the foundations and turbines, while separate vessels install the in-field cables and export cables going to shore. The case selected used jacket foundations installed 45 km into the British sector of the North Sea, with water depths between 29 and 41 m.
Installation composition and batch size	The compositions define to what level the turbines are assembled before being collected by the installation vessel, and they differentiate between bunny ear, full rotor star, or separate components [47]. Sarker and Faiz [53] defined it as methods and added towers partially or fully assembled. Combining the installation vessel's deck capacity, turbine dimension, and weight determines the batch size. The installation composition chosen was batches of four complete turbines consisting of separate parts with a fully assembled tower, a nacelle with the hub, and three separate blades as described by Vis and Ursavas [47], Sarker and Faiz [53], Jiang [103]
Installation vessel	The installation vessels differentiated between the self-propelled jack-up vessel (JU) or jack-up barge. These are selected based on either the turbine (dimensions, weight, and composition) or the surrounding environment (harbor, foundation, water depth, or even power lines crossing the in-sailing) [47,55,61]. Barlow, Tezcaner Ozturk [104] further expanded on the installation vessel capabilities such as crane, jacking legs, or deck space. The vessel chosen for this case was a six-legged JU conducting two separate campaigns, one for the foundations and later for the turbines, bringing them to the offshore on-site assembly location where the turbine's main components are then assembled by utilizing the vessel crane [23].
Commissioning vessel	The commissioning vessels ensure that teams have access to the turbines while finalizing the turbine modules at their offshore location and maintaining the completed wind farm [105]. These vessels have different features, e.g., crew transfer vessels are granted access by the foundation ladders [106]. Here, a service operation vessel with a gangway was chosen to directly provide access to the foundation platform.

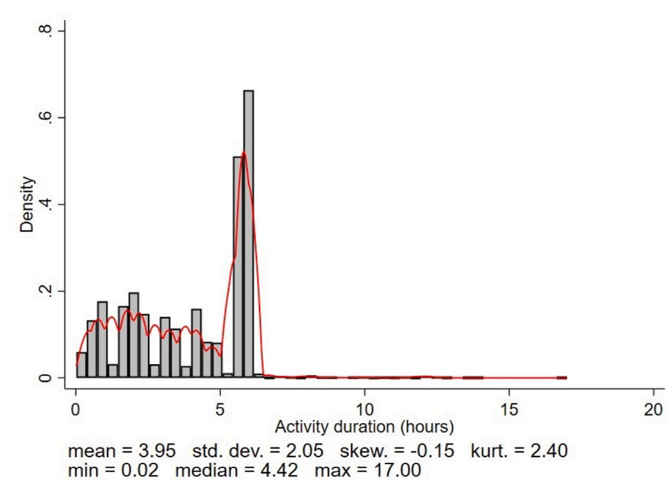


Fig. 2. Statistical distribution of activity duration.

offshore campaign started in PW 12. A batch of turbines was planned to continuously leave the harbor every week from then on, buffering the port with two batches, leaving the harbor workforce to wait in between in having filled the installation vessel buffer of prepared components.

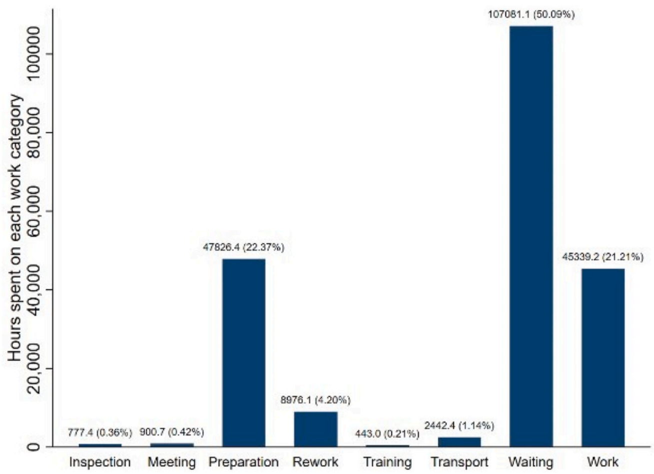


Fig. 3. Duration of activities for each work categories.

There was a positive peak in productive hours, building up just before PW 50. The development of COVID-19 in Europe started in PW 50.

4.2. Understanding the non-value-adding activities

The results from the second unit of analysis are presented in section 4.2.1,4.2.2, and.

4.2.1. Expanding the waiting time category

Approximately half of the project duration is spent on waiting - totaling 107,081 out of 213,786 h. A reason is provided for 95.76% of the waiting activities, however, the remaining 4.24% remain unspecified. The explanation was classified into 16 different delay factors based on the unit of analysis (Table 3). In terms of time spent on waiting, the five most important reasons for waiting are weather, previous tasks, vessel, components, and location. In aggregate, these five categories account for 82.23% of the waiting. The most prevalent and impactful trigger for the waiting activity was the weather. As seen in Table 4, 10,450 of the waiting activities, or 44.69%, were due to weather. Analogously, around 49,703 h or 46.42% of the accumulated time spent on waiting was caused by weather. Previous tasks and vessels account for 11.94% and 11.37% of the time spent on waiting. Components and location are responsible for 7.19% of the waiting. The COVID-19 pandemic ranked thirteenth as an unexpected condition in the waiting reasons category. It instigated 81 waiting activities, which in aggregate made up for 447.25 h (0.42%).

4.2.2. Investigating runtime of delaying factors

Figs. 6–10 showcase the development in time spent on waiting caused by each of the categories. The graphs have the project weeks along the x-axis, while the y-axis on either side relates to the hour density of the delaying factor. The COVID-19 pandemic was emerging in China around PW 42 (November 2019), and started its development in Europe at PW 50 (February 2020), continuing beyond the project closure.

Fig. 6 (a) compared weather and vessel to see if these had similar behavior, which was not the case. It is possible to see how waiting hours increase each time a vessel is introduced to the project, this happened in PW 12 for the installation vessel, and at about PW 25, this vessel encountered engine issues. On the other hand, the weather peaks from PW 38 to PW 46 reveal autumn and winter's effect on productivity, lasting till spring in PW 52. Location in Fig. 6 (b) revealed inconsistent waiting due to locations not being available for various reasons, although the data available did not allow further investigations. Observations, however, revealed that the workspace being occupied by other teams contributed to this.

Fig. 7 (c) compares components and parts as both are affected by the international supply chains; their hour densities are different, having parts represented by the right-side y-axis, the x-axis represents the number of hours. The missing inbound component deliveries were caused by waiting in four peaks, starving the workstation. Further explanation was not available. The minor disruption was related to minor issues such as quality issues. Instead, the parts were not as disruptive in terms of hours; accessibility through local sourcing could be a reason. Fig. 7 (d) shows the waiting-related tasks handed over before completion. This is among the five most significant delay factors that indicate hand-over issues among both teams and project phases. The graph in (d) does not reveal learning among actors or project phases.

Fig. 8 (e) shows the documentation issues being disruptive at the beginning of the offshore campaign. The reasons were not further specified but could be related to the legislative or contractual requirements to receive permits to access the field. Between PW 30 and 40, there is seemingly a link between the waiting for documentation and later information from the involved parties. The last significant disruptions caused by information were directly linked to the COVID-19 pandemic. Fig. 8 (f) shows equipment and tools in comparison, the left y-axis is the hours related to waiting for tools. The ratio can be explained with the accessibility of tools, which, similar to parts, can be locally sourced. Missing or faulty equipment had a significant impact on the waiting. The equipment peaks in PW 24 and 41 were related to breakdowns disrupting the offshore campaign. The PW 48 peaks in waiting time for both equipment and tools were associated with a spare parts shortage.

Fig. 9 (g) shows how waiting for skilled labor was divided between manning and competencies. The peaks in PW 26 and 30 related to a competence issue, where skilled labor was required, specifically. Between PW 48 and the closure of the project, a shortage in resources occurred due to COVID-19. The graphs show realized time, the increasing number of non-realized hours was not registered. The non-realized hours were related to the border closures in Europe (e.g., Denmark, Poland.), affecting resource availability. Fig. 9 (h) shows the relation between safety disruptions and unexpected events (COVID-19). The safety peaks in PW 19 and 34 are related to safety incidents. PW 22 contained an accident causing a lost-time case, and all three occurrences disrupted all labor in the adjacent locations. The COVID-19 disruptions represented 0.42% of the total waiting hours. The quarantining and uncertainties around it created disruptions despite additional measures such as gloves, respiratory protection, and cleaning.

Fig. 10 (i) represents 4.24% of the total distribution occurring throughout the project. Fig. 10 (j) planning related to communication, directions, and information between management and teams caused waiting time for the teams. The peak in PW 45 related to a permit revoked due to a complete stop in the offshore campaign.

5. Discussion

The latest existing knowledge of what causes low productivity in offshore wind projects can be attributed to Koch [21], who pointed at weather, product technology, site features, and processes as reasons for delays. The results presented in this research expand beyond this knowledge. The weather is the most considerable delay factor in terms of its hours (49,703.42 h). None of the results pointed towards the product technology, and this will not be pursued further. The site features could be related to a part of the location factor, Lerche, Seppänen [60], Irawan, Song [101] support this by pointing at the technicalities around the locations. Koch [21] combines both project phases and activities as "the processes," and this research supports this, but not for the same reasons. Rework activities (8976.1 h) could be considered related to the processes, likewise, is the delay factor previous task (12,780.25 h). Seemingly, it was a more significant problem for the case organization that incomplete activities were passed on downstream.

Our findings extend the knowledge of delaying factors in offshore

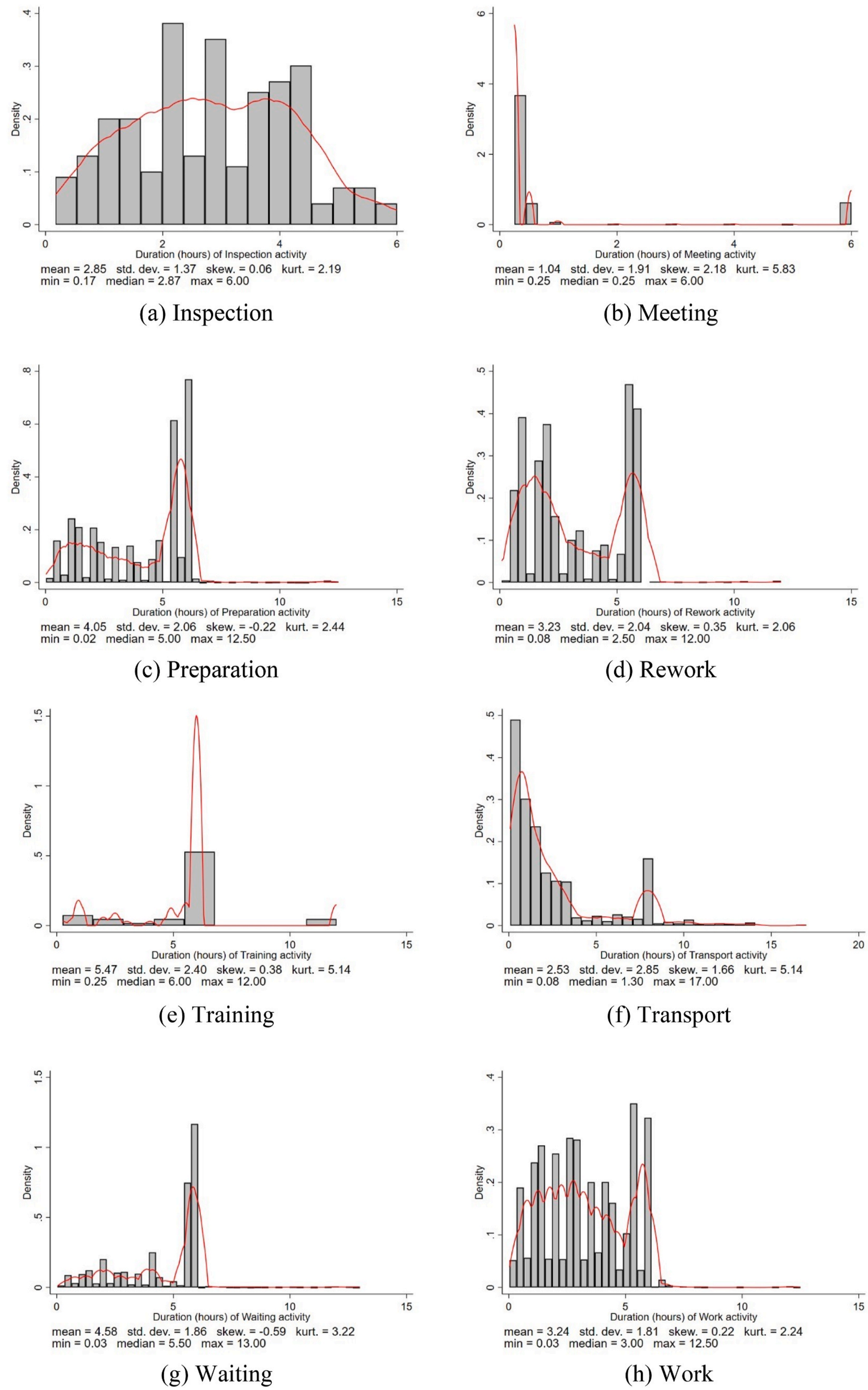


Fig. 4. Statistical distribution of activity duration for each work category.

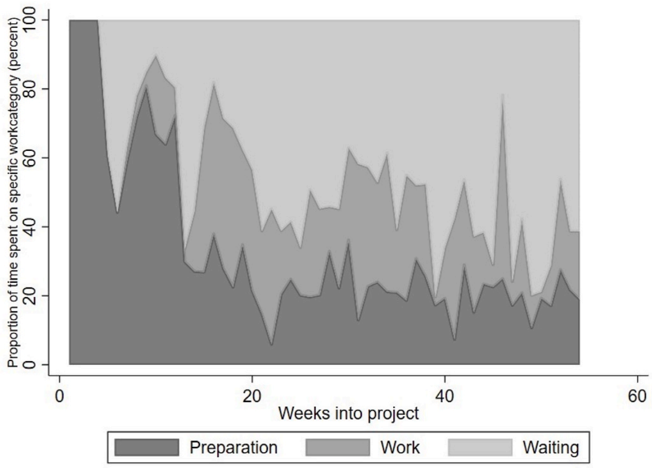


Fig. 5. Comparison between time spent on preparation, work, and waiting.

Table 4
Reasons for waiting (sorted according to rank).

Delay factor	Rank	Activity		Duration	
		Frequency	Percentage	Hours	Percentage
Weather	1	10,450	44.69	49,703.42	46.42
Previous task	2	2983	12.76	12,780.25	11.94
Vessel	3	2387	10.21	12,177.61	11.37
Components	4	1483	6.34	7702.75	7.19
Location	5	1374	5.88	5686.1	5.31
Equipment	6	1024	4.38	4996.53	4.67
Unspecified	7	992	4.24	3839.07	3.59
Permit	8	708	3.03	2902.6	2.71
Manning	9	447	1.91	1983.06	1.85
Planning	10	689	2.95	1856.49	1.73
Safety	11	336	1.44	1357.01	1.27
Information	12	208	0.89	802.72	0.75
Unexpected conditions (COVID-19)	13	81	0.35	447.25	0.42
Parts	14	78	0.33	289.86	0.27
Documentation	15	70	0.3	273.49	0.26
Competence	16	51	0.22	241.78	0.23
Tools	17	23	0.1	41.1	0.04

wind projects, enabling operational managers in stabilizing productivity as preconditions has done for construction [36,110].

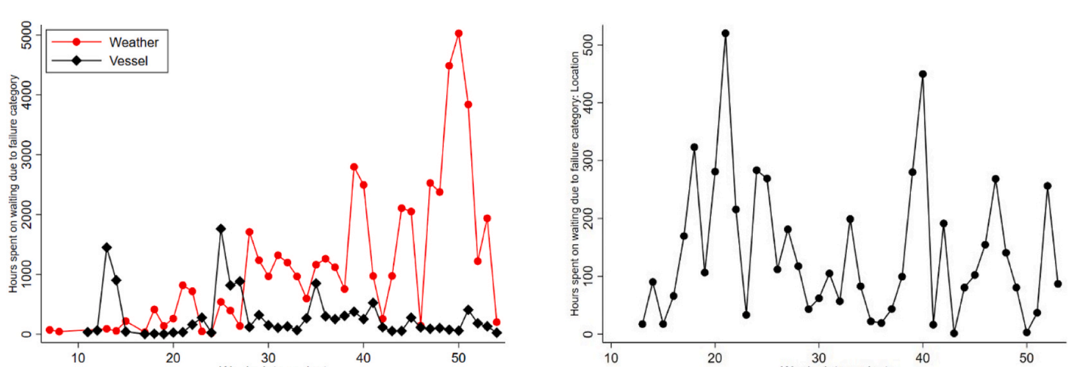
5.1. Implications to managing offshore wind projects

Of the 213,786 h, 21.21% were productive hours, and 78,79% were non-productive hours, whereof 50,09% would be considered waste. Weather alone represents 20.9% of the total time, which supports the attention weather calculations has been given through time [22]. But as existing planning methods have continuously tried to predict and limit the impact of weather [49,51,55,111], it is interesting why such predictive methods were not reflected in the results. Besides weather, the results also reveal a potential for significant improvement of at least 30%. E.g., planning and permits combined represent 4.44% of the total waiting time, which supports Lacal-Arántegui, Yusta [23]'s argument that current planning methods are not adequate for future turbines.

The findings revealed that waiting was caused by both materials (including components and parts) and resources (including manning, competences, equipment, tools, and vessels). The receiving facility harbor facilities have physical limitations, restricting the inventory and the number of main components on-site [49,101]. Interestingly, the results also show this as peaks of starvation of the workstations in Fig. 7. Fig. 5 reveals a significant variation throughout the project weeks and its effect on productivity. This is particularly interesting when considering past knowledge of learning curves, with Thomas, Mathews [112], assuming that productivity would increase throughout the project as people gain more experience. Another interesting finding is the time spent preparing for the first ten project weeks; this could also indicate that harbor activities are considered preparation. These results reveal similarities to productivity levels seen in other labor-intense projects [18,112] and emphasize the need for alternative planning methods not only in offshore wind projects.

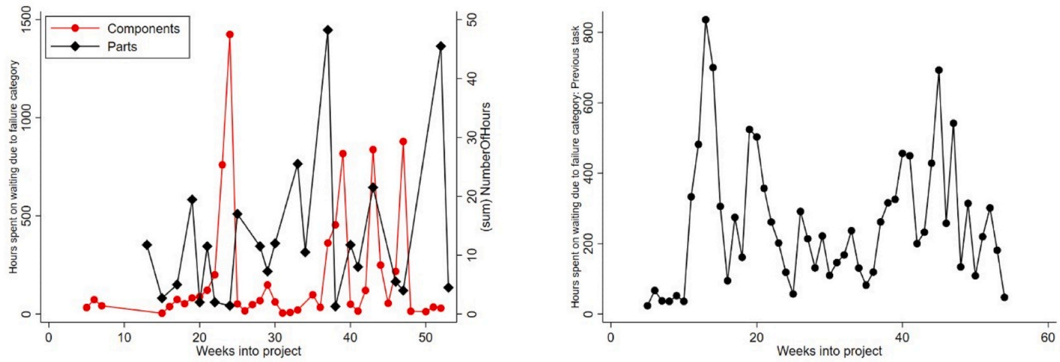
5.2. Implications of a disaster (COVID-19)

The disruption of COVID-19 supported past arguments about the time urgency of an emergency, disaster, or occurrence of undesired events [34,72]. In aggregate, COVID-19 made up for 447.25 h (0.42%), its impact was felt in relation to the political decisions across Europe, particularly border closures, which limited resource movements. That COVID-19 occurred late in the project also limited the impact on the material supplies as the last components were placed on inventory before the pandemic's development in Europe. There was a spike in waiting time for equipment and tools around project week 50, which was related to the lack of spare parts. It is impossible to determine if this was due to COVID-19 or a coincidence based on the available data.



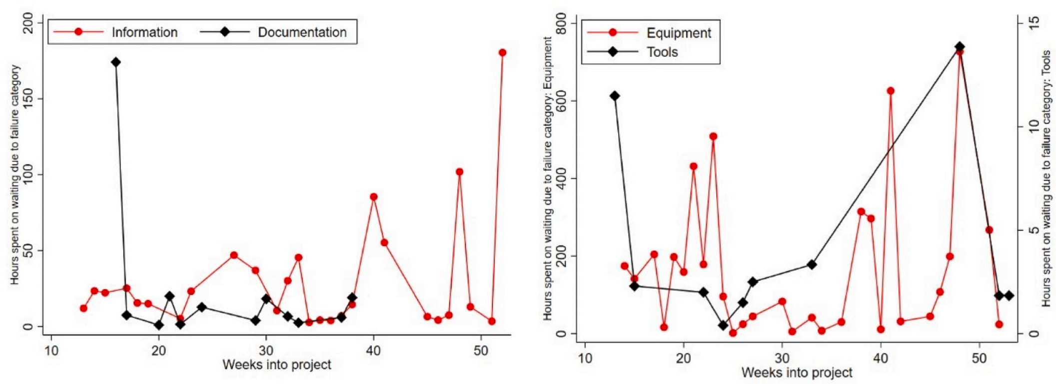
(a) Weather & vessel compared (b) Location

Fig. 6. Development time spent on waiting for each delay factor.



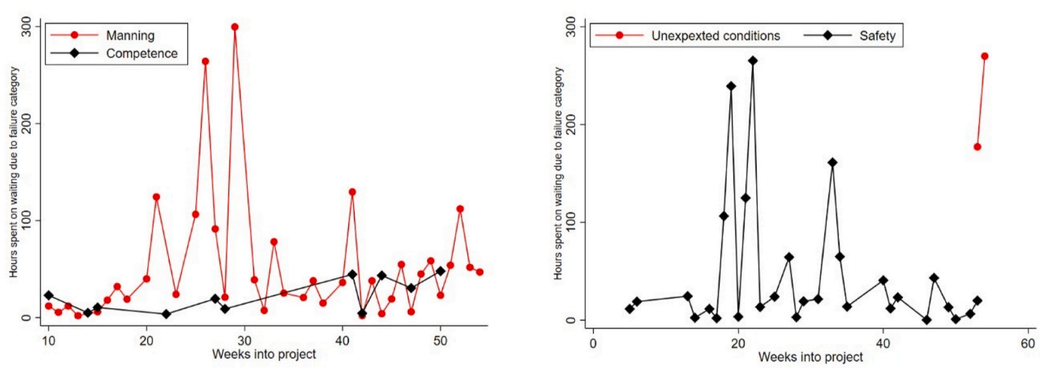
(c) Components & Parts compared (d) Previous task

Fig. 7. Development time spent on waiting for each delay factor – Continued.



(e) Information & Documentation compared (f) Equipment & Tools compared

Fig. 8. Development time spent on waiting for each delay factor – Continued.



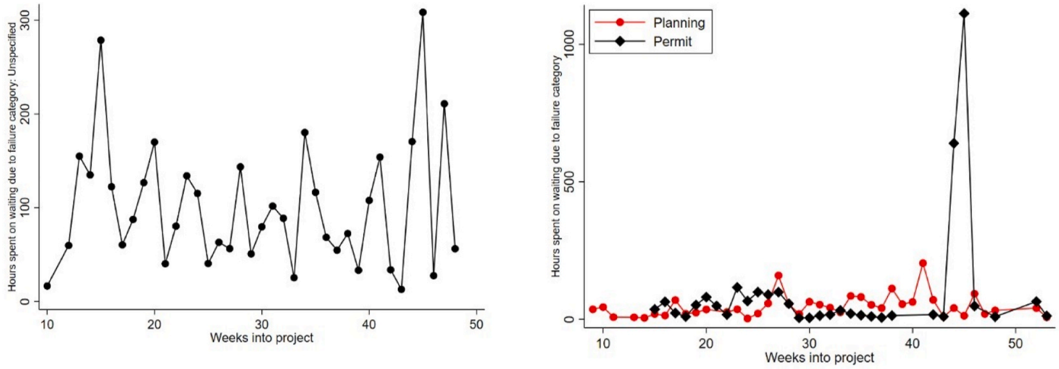
(g) Manning & Competence compared (h) Unexpected conditions (COVID-19) & Safety compared

Fig. 9. Development time spent on waiting for each delay factor – Continued.

5.3. Limitations of the study

Comparing the first unit of analysis with those applied similarly during work sample studies [13,18,113,114], reveals that our unit of analysis was adjusted, given that the work sampling registrations for talking were not available. Another difference was the lack of applicability and inaccuracy among trades [62]. But where the work sampling method provides a picture of the labor productivity, this study has strengthened by displaying the overall project performance. This was supported by Neve, Wandahl [18], who found that investigating productivity was not trade-dependent. The second unit of analysis is unpreceded within the offshore wind, which could be seen as a limitation. But from an explorative perspective, a strength, given there were no prior biases regarding the delay factors.

Limitations to the results, the results only consist of flow variability [14], as waiting was the primary reason for non-productive hours.



(i) Unspecified (j) Planning & Permit compared

Fig. 10. Development time spent on waiting for each delay factor – Continued.

Process-time variability [115] could have been either undetected, mislabeled, or within the work and preparation hours. In addition, unspecified waiting represents 3839 h, equivalent to 3.59% of the total waiting time, which might be relevant for an operations manager but is not considered suitable for the results shown. With regards to the COVID-19 pandemic findings, it is a possibility that some of the progress reports did not contain the complete overview of the events', as non-realized hours were not included, they were only available by the end of the case study.

6. Conclusion

The study of the value-adding and non-value-adding activities provided an insight into how hours are spent during a modular offshore wind turbine project. The results extend the body of knowledge, by developing and testing the units of analysis on a case of historical data. The delay factors further expand the body of knowledge applicable to practitioners and academics, providing them with measurable parameters for investigating delays in future projects. By utilizing the delay factors as part of a management and control system, decision-makers can reduce data complexity. This would enable educated decisions that can bring down variability and improve offshore wind project productivity. Further research would be required to investigate if these results are generalizable across other renewable energy projects.

Credit author statement

Lerche, J.: Writing – original draft, Writing – review & editing, Methodology, Data curation, Formal analysis, Conceptualization, Project lead, Lorentzen, S.: Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Enevoldsen, P.: Writing – original draft, Writing – review & editing, Methodology, Neve, H.H: Writing – original draft, Writing – review & editing, Methodology.

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.

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