First Lean, then modularization: improving the maintenance of offshore wind turbines

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Abstract

Purpose – This paper aims to explore how maintenance tasks can be planned and executed in a smarter way and, consequently, how the operations and maintenance of offshore wind power installations can be improved through modularisation.

Design/methodology/approach – This is a case study of one of Europe's leading offshore wind power operators with more than 1,000 wind turbine generators in operation. By focusing on this company, in-depth insights into its operations and maintenance processes are investigated.

Findings – Lean is identified to constitute an important first step before the modularisation of maintenance tasks. The modularisation of the maintenance of offshore wind farms is identified to reduce preventive maintenance times.

Practical implications – The paper develops a process to identify the resources needed for maintenance before the modularisation of maintenance tasks and resources can take place. The authors also establish a foundation for the development of a software tool to support the development of the modularisation of maintenance tasks.

Originality/value – The present study contributes to the rather immature field of research on the operations and maintenance of offshore wind power. Furthermore, it adds to the emerging research area of service modularity.

Keywords Interviews, Wind energy, Maintenance, Offshore, Wind turbine, Optimization, Modularization

Paper type Case study

1. Introduction

In 1991, the world's first offshore wind turbine generator (WTG) farm was erected in shallow waters off the coast of Denmark, and since then, the offshore wind power industry has undergone rapid development. According to the European Wind Energy Association (EWEA, 2009), despite many unresolved technical issues, the development of the wind power industry has been shown via the increase in turbine sizes by a factor of roughly 100 in their first 20 years.

The advantage of offshore wind power installations is much stronger and more stable winds compared to onshore locations. However, the costs involved in producing electricity from offshore wind power are high compared to producing electricity from other energy sources, such as fossil fuels and even onshore wind power. In the future, subsidies may even be reduced, which would result in increased focus on the reduction

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of energy costs to make offshore wind power competitive with other energy sources. When looking at the overall costs of offshore wind farm projects, it becomes clear that the operation and maintenance (O&M) of WTGs makes up a significant amount, roughly 25-30 per cent of their lifetime project costs (Blanco, 2009; GL Garrad Hassan, 2013). Research on reducing O&M costs of offshore wind farms, however, is still limited (Hofmann, 2011; Utne, 2010).

According to our research, several studies have focused on the development of larger and more efficient turbines (EWEA, 2009). However, to reduce costs, it is important to focus on all aspects of the offshore wind value chain, meaning that the O&M phase should receive more attention. In addition to costs, the maintenance of offshore wind farms is a complex operation, as the weather plays a major role (Tavner, 2012). While high wind speeds are optimal for production, maintenance often cannot be performed under such conditions, as wave heights increase and entering turbines from vessels unsafe. This means that maintenance tasks must be constantly rescheduled, making maintenance difficult to plan.

This paper is based on a case study of a large wind farm operator in Northern Europe. In this study, the O&M is examined via interviews, participation and observations related to maintenance. The wind farm was commissioned in 2002, and since then, innovations have been undertaken to improve the O&M aspect of the value chain. One such innovation was based on a Lean project whereby production performance was improved.

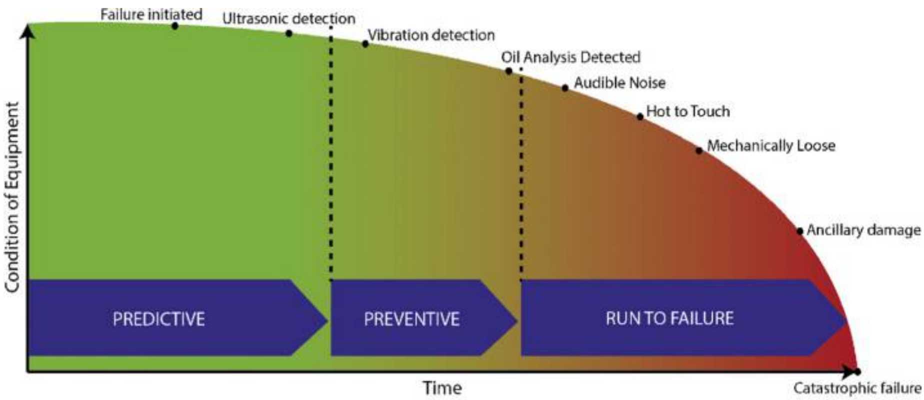
In this case study, we have been inspired to explore how modularisation can be used to structure the maintenance of offshore wind farms in a more efficient way. In combining the findings of this case study with those of the literature, we have developed a conceptual framework for modularising the maintenance of offshore wind farms. The purpose of this paper is therefore to explore how Lean techniques and modularisation in combination can improve the flexibility and reduce the complexity of maintenance planning for offshore wind turbines and, in turn, reduce O&M costs.

In Section 2 of this paper, we give an overview of the literature on offshore wind power maintenance, followed by a literature review on Lean techniques and modularisation theory. In Section 3, we will introduce the methodology and the case studied in this paper. The findings and development of work packages (WPs) are presented in Section 4, and in Section 5, based on the literature, a conceptual framework for modularising the maintenance of offshore wind farms is presented. In Section 6, we discuss the relevance and how it may be generalised. Finally, Section 7 concludes the research and considers its implications.

2. Theoretical background – the O&M of offshore wind turbines

Operations activities contribute to the high-level management of an asset, such as condition monitoring, electricity sales, administration and other back-office activities (GL Garrad Hassan, 2013; Moubray, 1997). Maintenance activities serve to keep an asset in full operation, and typical tasks include servicing, adjusting and repairing the physical asset and its subsystems. Maintenance activities can be divided into preventive and corrective maintenance, under which both scheduled and unscheduled activities can take place (Moubray, 1997; Murthy *et al.*, 2002). Preventive maintenance involves the preventive exchange, repair or renovation of components and systems to prevent break downs. It is performed routinely, often based on time or cycles, but it can also be based on the condition of the equipment. Corrective maintenance is reactive, meaning that it is performed when components or systems have failed or when a sensor sends an alarm (GL Garrad Hassan, 2013; Moubray, 1997; Murthy *et al.*, 2002). In Figure 1, an example of the gradual loss of function of a gearbox over time is visualised on a PF curve. A PF curve shows the condition of a piece of equipment from the point of defect (P) to the functional failure (F) (Moubray, 1997). The curve shows the three types of maintenance, namely, predictive (condition-based), preventive and run-to-failure (corrective). Examples of detection modes have also been added to the figure.

Whenever a system is in operation, maintenance most often has to be planned and scheduled to avoid breakdowns and catastrophic failures as illustrated in Figure 1. When planning maintenance, the execution of major preventive maintenance activities in accordance with other plans (e.g. shutdowns) has to be planned. Maintenance work has to be prepared and maintenance capacity needs to be determined. The scheduling of maintenance usually occurs over a short period and consists of determining the order by which activities must be executed (Dekker and Scarf, 1998). As with all other large equipment, a WTG must undergo preventive maintenance, which is done to prevent major damage to the asset. In the case of a WTG, e.g. the breakdown of a gearbox, blade damage or the failure of a bearing may lead to a collapse of the whole WTG. There is always a trade-off between costs and benefits when determining to which level preventive maintenance should be committed to an asset. If only a small amount of preventive maintenance is executed, maintenance costs may be reduced (Murty and Naikan, 1995). However, this will lead to more breakdowns, i.e. "run to failure" (Figure 1) and, consequently may result in less availability from the assets (in this case decreased production from the WTGs). On the other hand, if too much time is spent on preventive maintenance, production must be stopped more frequently, thus leading to a reduction of



Source: Authors' own based on information from Kittiwake (2013), Moubray (1997), Petersen *et al.* (2013)

Figure 1. The condition of a gearbox over time visualised on a PF curve

availability and an increase in costs. The optimal maintenance will therefore call for the right mix of preventive and corrective (breakdown) maintenance to achieve a high level of availability and low costs. For a wind farm, the right mix of preventive and corrective maintenance may shift several times throughout the lifetime of a wind farm, e.g. when condition of the turbines changes, the skills of employees change, or the costs and incomes change. The lifecycle of a WTG can be divided into five phases: consent, construction, commissioning, O&M and de-commissioning (GL Garrad Hassan, 2013; Poulsen *et al.*, 2013; Tavner, 2012). This paper focuses only on the O&M phase, which serves to ensure the safe and economic operation of a project throughout a 20- to 25-year lifetime (GL Garrad Hassan, 2013).

Each individual WTG can be regarded as an unmanned power plant where the main mechanisms consist of a rotor with blades, low speed shaft, gear box, generator, yaw system and controller (Figure 2). In addition, there are a number of other subsystems and supporting systems like control systems, cranes, lift, foundations, cables, transformers and other systems connected to the individual WTG. All of these mechanisms undergo preventive maintenance. For example, the gearbox is inspected in terms of oil analysis on preventive maintenance visits, while blades are visually inspected for cracks and wear, etc.

Access to individual offshore WTGs, compared to those located onshore, is a challenge due to weather issues and in general, weather conditions have a significant impact on the planning and execution of offshore wind farm maintenance (Byon, 2010; Orosa *et al.*, 2010; Tracht and Seuguep, 2011). First, depending on the type of transport (e.g. vessel or helicopter), transportation to a wind farm can be time-consuming. Second, wave heights may decrease accessibility to WTGs. This means that offshore wind farms are accessible only 50-70 per cent of the year (Breton and Moe, 2009), and that they can be inaccessible for many days due to harsh sea, wind or visibility conditions (Tavner, 2012). Accessibility is especially critical for corrective (or potentially unscheduled) maintenance, as an operator can have very little knowledge of when a failure might occur and thus cannot rely on steadily consistent maintenance checks. Furthermore, due to constantly changing weather conditions, the planning of maintenance activities can be difficult and subject to constant rescheduling. This means that when the window for performing maintenance is open, an organisation has to be ready to carry out the maintenance tasks. This also constitutes a major difference in relation to maintenance of onshore installations and to maintenance within manufacturing.

Through our literature review, we found that research on the O&M of offshore wind farms has been very limited and is currently in its early phases (Utne, 2010). Existing

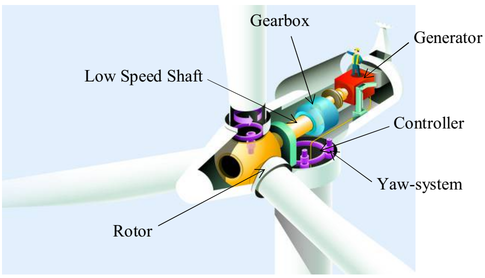


Figure 2.
The inside of a wind turbine (illustration by Vattenfall, text added by authors)

literature on maintenance and service within the wind energy sector appears to be scattered across various subjects, such as the development of sensors for oscillation (Caselitz and Giebhardt, 2005), decision theory (Sørensen, 2009) and mathematical models for planning of maintenance (Besnard *et al.*, 2009, 2011). Certain studies (Fischer *et al.*, 2012Nielsen and Sørensen, 2011) have sought to introduce well-accepted maintenance concepts such as reliability-centred maintenance (Moubray, 1997; Nowlan and Heap, 1978) into the wind energy sector. Our literature review reveals, however, that the success of such implementations has been modest at best.

Our study of Lean and modularisation can be used in the planning and execution of maintenance in the offshore wind sector, and it attempts to fill a gap in the literature by investigating how maintenance planning can be performed in a more structured manner when weather issues play a major role.

Service modularisation is a newly emerging research field (Dorbecker and Bohmann, 2013) that has inspired us to investigate how modularisation can be used to structure and systematise maintenance of offshore wind farms. In what follows, a short introduction to the concept of Lean is given and afterwards service modularity is discussed.

2.1 Lean in maintenance

Lean has been heavily applied in operations management to eliminate waste and generate value from the customer's view point. Lean is about creating flow, improving quality and improving maintenance [through total productivity maintenance (TPM)] (Womack *et al.*, 1990). Flow, quality and maintenance are grouped, as a lack of quality as well as improperly maintained equipment will stop the flow. Lean is a fundamental step in performing better maintenance, and that is why we address this issue in this paper. In addition, Lean is also about management and leadership (Davis, 2001), which plays a major role in maintenance.

"Lean maintenance" is somewhat of a new term; yet, its main principles stem from the maintenance concept TPM (Smith and Hawkins, 2004). According to Shah and Ward (2003), little has been published on maintenance optimisation, and Lean may play a major role in not only operations but also maintenance. In Lean, the fundamental pillars are maintenance, quality and flow, where the maintenance of equipment and the quality of material are essential to obtaining flow and result in quality products (Smith and Hawkins, 2004). Lean includes five basic principles, each of which is briefly presented here and discussed in relation to maintenance:

(1) *Specify value from the standpoint of the customer*: In WTG maintenance, direct customers include not only the purchaser of electricity but also the owners of the WTGs. The value for the owner lies in the maintenance processes for WTGs, which improve their reliability and energy output.

(2) *Identify value streams and eliminate non value-adding steps*: To optimise, it is important to know which activities create value and which do not. Lean uses a value-stream mapping tool (and similar tools are applicable in terms of maintenance) to map and visualise the value stream with regard to the challenges and imbalances in the supply chain.

(3) *Create flow*: When beginning a maintenance process, it should run until it is fully completed, with as few interruptions and stops as possible.

(4). *Make customers pull*: Perform maintenance neither too early nor too late but rather just in time. This will require good management skills and control systems.

(5) *Make continuous improvements*: To pursue perfection (Lean: kaizen). Standard operating procedures (SOPs) are important to reduce variations in maintenance task quality and times. Aside from having SOPs, it is important to foster a company culture which is focussed on continuous improvement.

Lean possesses a number of tools to improve flow, product quality and maintenance. In Lean maintenance, a tool such as value-stream mapping is essential to eliminate waste. In addition, performing standardised work helps unify procedures to increase quality and save time, and selecting the right methodologies for the creation of modules and maintenance kits is necessary to make maintenance more efficient. The 5Ss method (sort, set in order, shine, standardise and sustain) represent another powerful tool which can make daily routines much more efficient by putting extra focus on cleaning, sorting and the development of standards and attitudes for keeping the workplace systematically clean and well structured. Finally, single-minute-exchange-of-die (SMED) techniques from Lean can be used in offshore WTG maintenance to reduce setup times and when preparing new maintenance jobs.

Lean maintenance has been defined by Levitt (2008, p. 12) as the "delivery of maintenance services to customers with as little waste as possible, or producing a desirable maintenance outcome with the fewest inputs possible". Output here refers to reliability/uptime, output quantity, repeatability (less variation) and safety in relation to employees, the public and the environment. Inputs refer to labour, maintenance parts, management, contractors, energy and capital. The concepts discussed by Levitt (2008) are very much in sync with our approach in this paper; yet, this paper's combination of Lean and modularisation represents a new concept. This new concept is an extension of Bilberg and Hadar's (2012) research on Lean automation, which suggests focusing first on Lean to become effective and then on innovation automation solutions to become more efficient and productive. Lean is playing a role in sustainable production, where Lean tools can help reduce the environmental impact of manufacturing companies and where Chiarini (2014) sees TPM as one of the Lean methods. TPM is a method which aims to reduce machine breakdowns, and this is discussed by Lu and Yang (2015) in relation to highly automated production, where focus is on how to use Lean tools to optimise processes.

2.2 Service modularity

This study is also inspired by the literature on modularisation (Mikkola, 2006; Starr, 1965) and the modularisation of services (Voss and Hsuan, 2009). Traditionally, modularity has been understood as referring to the interchangeable nature of product components (Voss and Hsuan, 2009). However, the concept of modularisation has since been extended beyond the field of manufacturing into services (Voss and Hsuan, 2009). While maintenance is not a direct service, an organisation that performs maintenance can be understood to be offering a service to, for example, an owner of WTGs. In searching the literature for studies on the maintenance modularisation of offshore wind farms and maintenance modularisation in general, we were unable to find other research with this specific focus.

Modularity has mainly been used within the field of product development and manufacturing, wherein modularisation has allowed companies to supply a variety of products to consumers in a mass production context (Fujita, 2002; Starr, 1965, 2010). This can particularly be illustrated within the automotive industry (Jose and Tollenaere, 2005; Mikkola, 2006, 2003), where the concept of a common platform and modularity has been taken into account by combining components into different modules which again through interphases can be developed to a large variety of subassemblies or final products. For instance, as early as 1956 General Motors (GM) used a common platform wherein different modules for its Corsair models allowed the company to manufacture a large variety of automobiles (e.g. convertible sports cars, sedans, vans and even pick-up trucks) based on the same platform (Marion *et al.*, 2012). Fujita (2002) has developed a structured model that illustrates how different attributes can be shared within different modules so as to create different products as well as how modularity is often used when developing the architecture of a given product. Architecture means a product's functional elements, including its constituent parts and how they interact with one another.

Modularity has also appeared in other sectors, such as shipbuilding (Erikstad, 2009) and the computer industry (Baldwin and Clark, 2002). Fixson (2005) has discussed product modularity and its costs in relation to product, process and supply chain design decisions, while Brun and Zorzini (2009) have focused on product customisation via the use of modularisation and postponement. The concept of modularity in product and organisation design may not only help to create a flexible product design but also enable the design of loosely coupled, flexibly modular organisational structures (Sanchez and Mahoney, 1996). This is of particular interest in our research, which focuses on developing flexible resource modules that contains tools, spare parts, competences and SOPs to develop flexible organisational structures and to deliver flexible maintenance services in the offshore wind power industry, wherein weather changes have a major impact on the kind of tasks that can be carried out at sea and their timing.

Starr (2010) has argued that service modularity may represent a new and rich field for investigation. While research in this area is growing, according to Carlborg and Kindström (2014), there is currently a gap in the literature. The benefits of using a modular approach have long been known in the field of software engineering, where the reuse and variation of software modules have been used to develop new software functions in an efficient manner (Tuunanen and Cassab, 2011). Despite the clear potential of adopting a modular approach to services, the notion currently lacks a common definition, thus making the idea rather vague (Bask *et al.*, 2011).

According to Carlborg and Kindström (2014), traditional modularity involves the separation of objects into modules that, in turn, can be combined into customisable products. The objects in a service can be both physical and non-physical. Carlborg and Kindström (2014) sum up the work of Böttcher and Klingner (2011, p. 2), Davies *et al.*, (2007), Pekkarinen and Ulkuniemi (2008) and Ulaga and Reinartz (2011), as follows:

> In the service milieu, an object is often not the issue; instead, service is often defined as a process, with [a] service typically consisting of a combination of physical and non-physical elements integrated into various customer-specific configurations (Böttcher and Klingner, 2011, p. 2).

In the context of offshore wind turbine maintenance, this statement is precisely the case as maintenance is understood to be a service composed of both physical and non-physical elements that are integrated to comply with the operation of a given asset. According to Edvardsson *et al.* (2005), it is important to understand the resource structure of these needs, as the resources required in the service process must be identified and understood before modularisation can begin. We will illustrate this later in this paper through our findings from our field studies.

3. Methodology and case description

This paper involves the empirical study of a large offshore wind farm which has been in operation for 13 years in very rough sea conditions in the North Sea. The wind farm consists of 80 identical 2 MW WTGs, each of which could be studied independently. The wind farm is operated and maintained by Vattenfall Wind Power, which operates more than 1,000 WTGs as one of Europe's leading offshore wind power operators.

In this study, the case study method has been used, as Stark and Torrance (2005) have described it as the most suitable method for the study of topics lacking empirically based research. Furthermore, case studies are often used when developing new theory (Benbasat *et al.*, 1987; Gersick, 1988; Harris and Sutton, 1986; Van de Ven, 1989). Yin (2009) and Eisenhardt (1989) further argue that a case study should include multiple cases. However, Yin (2009) also finds that single case studies are suitable when there is an opportunity for unusual research access, which has allowed for in-depth examination, e.g. by participation in maintenance. Dyer and Alan (1991) argue that classic case studies (one case) should focus on one context exclusively so as to describe its various phenomena in rich detail. They further argue that such case studies are of good quality due to their detailed descriptions which allow for findings to be more easily understood and recognised in other research. We have also been inspired by Flyvbjerg (2006) who states that concrete, context-dependent knowledge is more valuable to science than predictive theories and generalisations. Thus, a single in-depth case study is good for learning something new. Furthermore, Flyvbjerg (2006, p. 8) states that "it is incorrect to conclude that one cannot generalise from a single case" (Flyvbjerg, 2006). Based on this information, we therefore decided to use an in-depth single case approach but to use a unit of analysis of 80 identical machines (WTGs), each of which could be studied independently.

In this study, we have had direct access to employees and all company data. Furthermore, we have been able to follow discussions with partners and suppliers who are actors in the offshore wind industry. This has helped to gain in-depth insight into the process of operating and maintaining offshore wind turbines.

To acquire knowledge of the O&M processes, both qualitative and quantitative research was performed. The research is based on our participation in the maintenance work of offshore wind turbine installations. During five visits to the wind farm, we observed and participated directly in maintenance activities. Field notes were taken, and summaries were confirmed by the technicians. In addition, nine semi-structured interviews (Brinkmann and Kvale, 2009) were conducted with the technicians, a site manager and the managing director. The interviews followed a guide, but conversation was open to subjects, which came up during the process. The interviews had two objectives: to understand the maintenance carried out at the wind farm in general, especially the tasks carried out during our visits to the wind farm; and to investigate how the company had carried out a Lean project and how this had affected the performance of the wind farm. Additional follow-up interviews were later conducted to clarify understandings.

The study has involved weekly visits to the company over a three-year period and in relation to conversations, participation in meetings and observations, a large number of field notes have been made and subsequently unveiled. Furthermore, various company reports and surveyed statistical data have been analysed to triangulate the data acquired via the interviews, conversations and observations. For example, after interviewing one manager, we looked at various economic and time-usage reports to confirm his statements on the results of the company's work. In addition, the alarm data from all the 80 WTGs have been analysed to confirm statements from an interview where it was stated that the number of alarms had decreased after the Lean project was initiated. The most frequent alarms, and thus the most consumptive resources in terms of corrective maintenance, were also identified. Finally, observations during the visits to the wind farm were confirmed in relation to the information retrieved through conversations with company members. This study has therefore used a number of different methods for gathering and verifying data.

The development of frameworks in this paper is first made by investigating and discussing a Lean project from the case company in relation to the case study. The Lean approach is then further developed and re-considered into WPs (illustrated in Figure 4). Results from the Lean project are discussed, reflected upon and brought further in Section 5, where the literature of modularisation has been used as inspiration for the conceptualisation and development of resource groups and modules/resource packages (RPs) to meet the tasks of maintenance in the offshore wind power sector.

3.1 The operation and maintenance department

The department at Vattenfall that operates and maintains the wind farm used in this study is run by a site manager who oversees two alternating teams of eight internal technicians, each of which works 12-hour shifts for a full week. During summer, external technicians are hired to help cover the workload. In addition to this, a number of local and shared support functions help in the operation of the wind farm.

The department handles roughly 750 work orders every year, consisting of both preventive and corrective task (from now on called maintenance tasks). The time spent on each task varies greatly, from failure-finding tasks that can take a few hours to a full working day, to preventive maintenance checks lasting three to four work days. There are two types of service checks: small service and large service. In the small service check, which uses two technicians for one full day (thus two working days), various systems in the WTG are checked, lubricants are refilled and the turbine is checked for oil leaks. In the large service, which uses two technicians for two days (thus four working days), also safety systems are tested, certain time-directed components are replaced, bolts are tightened and the equipment is cleaned.

3.1.1 The Lean project. In 2011, a new site manager for the wind farm was hired, and he wanted to know how much time was spent on different groups of maintenance tasks. The technicians were asked to log their work tasks. Based on this information, it was decided to reduce this wasted time, while at the same time, looking for other areas where such wastage could be reduced. To do so, Lean principles were used. The company took a practical approach in their application of Lean and did not use a systematic Lean manual but instead relied on the craftsmanship and diverse background of its technicians. When analysing the maintenance tasks, the activities were sorted as value-adding; not value-adding, but necessary; and pure waste (Lean: MUDA). The primary aim of this sorting was to reduce two elements: pure waste, such as waiting times, redoing failed tasks, as well as time spent on searching for tools/material, and performing unnecessary maintenance tasks; and waste which could be regarded as necessary, e.g. transportation, planning activities, transitioning from one task to another and reading and investigating service manuals.

The purpose of this process was to perform maintenance tasks effectively (to do the right things) in an efficient manner so that a continuous flow of activities was achieved. To do this, SOPs were developed whereby each individual technician on the maintenance teams could agree on procedures for certain tasks to increase quality and save time. Parts of these SOPs were a 5S programme in which tools and materials were relocated to agreed-upon positions. In addition, a systematic work process was introduced where technicians were encouraged to improve efficiency and thereby to reduce waste. Finally, a restructuring of the maintenance tasks and a systematic review of group competencies were part of this process.

The Lean project resulted in several improvements, which will be presented in the next section. Today, maintenance of the wind farm is performed according to a "work smarter, not harder" philosophy, and the organisation has implemented a culture in which maintenance tasks are continuously being improved (i.e. kaizen).

4. Case study of Lean and development of work packages for maintenance

Our interviews with technicians and management, our observations and our survey of data at the offshore wind farm revealed how the O&M organisation had been able to reduce the time spent on preventive maintenance via a Lean project when each of the 80 offshore WTGs was serviced two times each year for time-based preventive maintenance.

The wind farm's maintenance team had gained a clear view of how to structure maintenance tasks and distinguish which were most integral to the successful operation of the farm. The maintenance tasks were therefore divided into three categories: simple tasks, medium tasks and special tasks. Each is described as follows:

(1) *Simple tasks*: These were repetitive tasks that had to be carried out recurrently and were relatively easy to complete (e.g. service checks, tightening of bolts, topping up of lubrication and cleaning).

(2) *Medium tasks*: These tasks required more knowledge and were therefore more challenging (e.g. diagnosis of malfunctions and failure corrections of WTGs). The complexity of medium tasks was quite high, often higher than that of special tasks.

(3) *Special tasks*: These tasks required special training, knowledge or equipment to perform (e.g. identifying failures in connection to a generator and repairing). These tasks were not necessarily complex, but due to either safety issues or the requirement of expensive equipment, they required special training.

Of these tasks, the company chose to outsource its simple and special tasks, finding them too costly to maintain in-house. By performing medium-level tasks in-house, key knowledge required for the identification of failures and correction were retained. Through interviews with management, we found that the internally employed technicians mastered the process of quickly identifying the root cause of failures and subsequently correcting the failures. This knowledge was important to retain in-house, as external technicians would not be able to obtain such knowledge quickly, nor would they possess the competencies to correct problematic issues as these required significant experience working on the specific wind farm.

4.1 Restructuring of maintenance tasks

At the outset of our study, we observed how the biannual servicing of the WTGs followed an Original Equipment Manufacturer (OEM) service manual, as legislation states that the maintenance of WTGs in Denmark must be carried out according to the OEM's guidelines. However, when the warranty period expired, the company implemented its own service organisation, which gradually became more experienced and therefore began to challenge the sequencing of the maintenance programmes and tasks provided by the OEM. Inspired by the Lean theory (Bicheno, 2004; Rother and Shook, 2003), the company began grouping tasks either by physical proximity or in a way that technicians' waiting times could be minimised as travelling time represented a major cost to the company. The tasks were thus divided logically so as to reduce this issue. The original service manual was restructured by dividing maintenance tasks into two kinds: those that required normal offshore training and those that required additional training. For repetitive maintenance tasks, SOPs were developed to ensure that these tasks were carried out in the same way to increase the quality of the work performed.

4.2 Development of work packages

When planning specific maintenance tasks, the management of the wind farm found that the technicians spent too much time packing specific tools and spare parts. This also occurred during all other maintenance activities, such as when correcting failures or conducting maintenance campaigns in which either new equipment was installed or components were replaced or renovated in a large number of the 80 WTGs. During our visits to the wind farm, we observed how the technicians handled the necessary equipment, tools and spare parts manually, and how they often had to search for the right tools.

Therefore, management decided to launch a programme for the development of different WPs to fit specific tasks. Specific tool lists were also developed for various maintenance tasks, and several WPs were assembled and made ready for specific tasks to be carried out. In this way, roughly 10 different WPs were developed. Common hand-tools such as screwdrivers and socket spanners were located in each of the 80 WTGs and therefore were not needed in the WPs, but special tools such as torque wrenches, or specially designed tools used to carry out a specific task, were placed in them. Such measures were related to the SOPs and the 5S methodology (Bicheno, 2004; Levitt, 2008), wherein tools and components are to be placed in a suitable location to make them easy to find. In certain WPs, new SOPs were developed to ensure that technicians would carry out a task in a specific way.

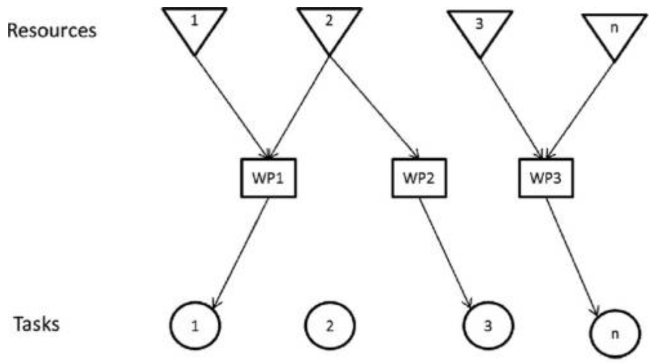
After developing these WPs, the technicians rarely forgot to bring the required tools. They also found it easier to prepare for their workday at the offshore site. From our interviews, we also noted that the development of SOPs increased the quality of the maintenance, which could be measured in the number of alarms that went off. From our analysis of the alarm data, we observed that the number of alarms was reduced by approximately one-third from when the project began in 2011 to 2014.

The improvement process that was observed in the case company is depicted in Figure 4. This figure illustrates how the required resources for specific tasks were identified and then grouped into a number of WPs. These resources included tools, spare parts, competencies and SOPs (illustrated with numbers in triangles). The same resources could be used for multiple WPs (squares), while each WP could be used only for a single task (circles) (Figure 3).

4.3 Results from the lean project

As mentioned above, the annual large service was divided into two parts: one that required common offshore training and one that required additional training. This was done to avoid special training for all technicians, which might include learning how to service high-voltage equipment, such as a transformer, or how to service the lift. In doing this, time spent on training was reduced together with the continuing costs involved in the training and education of technicians. In addition, this made it easier for management to outsource certain simple tasks to external providers.

From 2011 to 2013, the company achieved the following improvements which are summarised in Table I.



Notes: Resources identified were used in WPs used for single tasks. Task number 2 has no arrows leading to it, which illustrates that not all tasks were assigned a WP

Figure 3. Depiction of the improvement process observed in the case company.

Table I. Performance improvements after the lean project

Performance indicator	Before	After lean project
Time for scheduled service (%)	100	75
Number of crew vessels	3	2
Availability (%)	96	97.7
Number of alarms (%)	100	67

It is important to note that the increase in availability from 96 to 97.7 per cent is remarkable and very rare for an offshore wind farm as such availability is usually only observed at onshore wind farms (van Bussel, 2002). It should also be noted that, at the time as the Lean project was taking place, the WTGs were also given a few upgrades. For instance, an automatic lubrication system for the main bearing was installed and helped to save time in service visits, as it was no longer necessary to manually lubricate the bearings. However, our investigation of annual company reports and further interviews with the site manager and the managing director have illustrated that the main benefits were achieved from the Lean project.

4.4 Reflection on the results of the lean project

The O&M organisation was able to improve its performance substantially and increase the quality of the work by restructuring annual maintenance tasks and introducing WPs. In addition, by restructuring maintenance tasks and grouping competencies, management found it easier to outsource simple and special tasks.

During our field study of and visits to the offshore wind farm, we further observed how the restructuring process reduced the need for craning equipment, tools and spare parts from a vessel, as well as from the nacelle and back to the vessel. Craning is typically a time-consuming process in the offshore wind power sector. For instance, we observed how a craning operation could easily take 15 to 20 minutes to complete. The restructuring of service tools into modules had another positive result. The required equipment became lighter, as only the necessary parts were brought to the WTGs, which reduced the need for heavy manual handling inside the turbine and nacelle where there is limited space available for work. In turn, the time involved in craning equipment from the vessel to the WTG was also reduced, as there was less equipment to transport.

As mentioned above, the case company was able to achieve substantial improvements in its operations inspired by Lean concepts. However, we believe that a more structured approach could bring even further improvements to the O&M of offshore wind power installations, and we will explore this in the next section.

5. Conceptualisation – the development of a framework for maintenance modularisation

Based on the concepts of modularisation (Fixson, 2005; Starr, 1965, 2010) and service modularisation (Bask *et al.*, 2011; Carlborg and Kindström, 2014; Voss and Hsuan, 2009), we will in this section introduce the development of a conceptual framework of how to systematise and structure resources and tasks for O&M in the offshore wind power sector.

First, as stated by Edvardsson *et al.* (2005), it is important to understand the resources that are required to complete a given service. As this can be quite a cumbersome task, we suggest first using Lean to eliminate possible waste and then to proceed with a modularisation process.

5.1 Applying service modularity to the maintenance of offshore wind turbines

In this study, we have identified two areas in which modularisation could be developed for maintenance in the offshore wind power context. In relation to the first area, we have identified that modularisation can be used in the restructuring of maintenance tasks, what we will denote as "task modularisation". In relation to the second area, we have identified that modularisation can be used to structure resources, what we will denote as "resource modularisation". The latter refers to the development of WPs that we observed being produced in the case company. In the following, the two modularisation areas will be discussed.

5.1.1 Task modularisation. In our empirical study, we observed how the case company restructured maintenance tasks, such as service visits, to save time. This restructuring was based on management's and technicians' intuition in relation to moving from task to task inside the turbine during a service visit. We have therefore developed a structured method to develop maintenance tasks in modules that follows a three-step process: first, identify the modules of tasks; second, identify the required competencies; and third, solve the puzzle so that the sequencing of modules reduces waste and makes the service check more efficient. In Figure 4(a) simple flowchart of this process is presented. Please refer to Figure 6 for an illustration of the standardised list of maintenance tasks compared to the modularised tasks.

5.1.1.1 Step 1: identification of the modules of maintenance tasks. To restructure maintenance tasks, it is important to identify which tasks are mostly related to each other, as well as to develop a workflow that makes it easy for the technicians to carry out these tasks. Based on our observations in the field, we suggest including up to six or seven tasks in each module to increase the flexibility. A module represents a group of tasks, which is depicted by the small squares on the right hand side in Figure 6. As illustrated in Figure 5, each of the two technicians will in this instance carry out both individual and shared modules. A shared module, which is depicted by a rectangle in Figure 5, consists of maintenance tasks that need to be carried out by two technicians who are working together on the tasks.

5.1.1.2 Step 2: identification of required competencies. After creating modules of the maintenance tasks, the competencies required to carry out these modules should be identified. This is done to group together modules of tasks that require the same kinds of competencies. In this way, modules of tasks can effectively be divided

Figure 4.
A simple flowchart of the three-step task-modularisation process

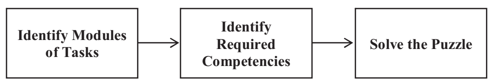
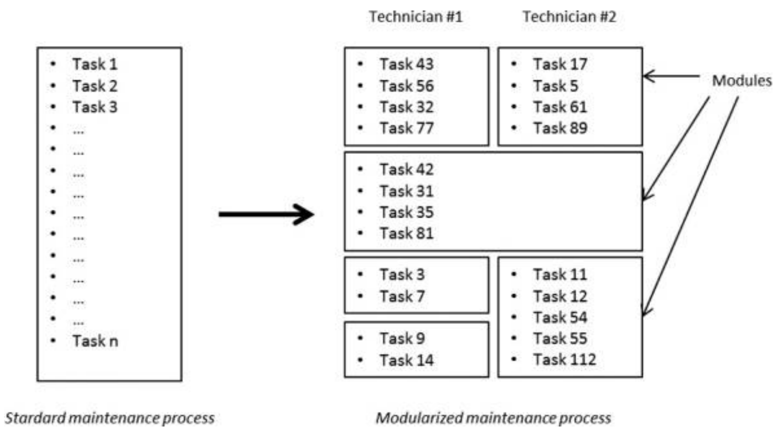


Figure 5.
Illustration of the modularisation of task process. Please note that the task numbers are random



between the technicians, each of whom holds different competencies. Modules of tasks that require a higher level of training and education can be grouped to take place on one day, while tasks that require basic training and education can be grouped to be completed on another day.

5.1.1.3 Step 3: solving the puzzle. After identifying the competencies required for each of the modules created in step one, it is then possible to start building the new service manual. This can be understood as a large puzzle with many pieces that must fit together to ensure both the lowest waiting times and the highest efficiency. In this puzzle, a number of alternatives are to be developed and finally the best solution can be chosen.

5.1.2 Resource modularisation. Resources can be both tangible and intangible and must each be clearly identified, as modular maintenance architecture depends on this information. In our suggested approach, we propose the following steps: the identification of resources needed to carry out certain maintenance tasks, the pooling of resources into resource groups and the creation of modules in the form of RPs. We have used the term RPs instead of WPs due to the fact that the WPs relate to a single, specific task, whereas the new RPs can be used for multiple tasks. These steps, which are depicted in Figure 6, are described in more details below and are later illustrated in Figure 7.

5.1.2.1 Step 1: identification of resources When identifying resources, there are two ways to approach the process. One can look for available resources among the employees (e.g. in the warehouse), or one can look for the required resources to fulfil the

Figure 6. A simple flowchart of the three-step resource modularisation process

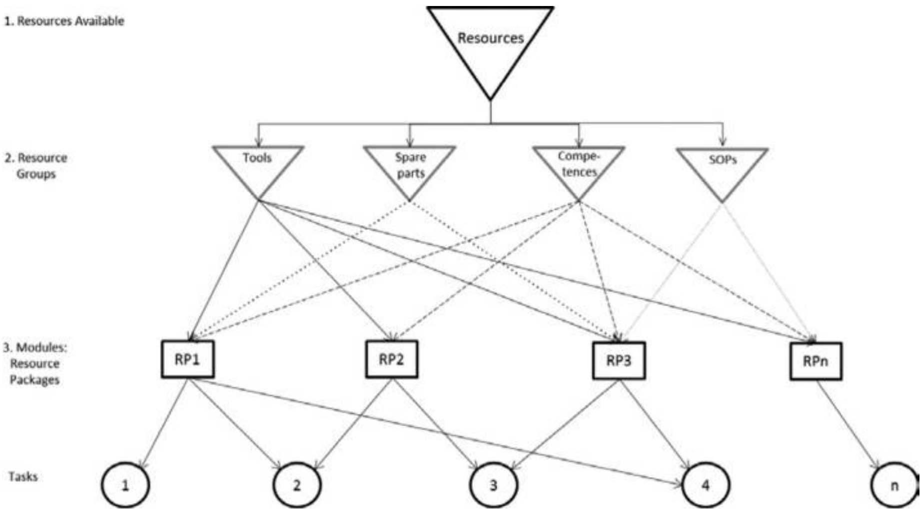


Figure 7. Illustration of the modularisation of the resource process

maintenance tasks. We propose a mix of these two approaches, as both have benefits. When identifying required resources, one must be sure to map all required resources, afterwards checking whether they are available. If the resources are not available to the company, they will have to be acquired. Mapping employees' competencies is also important, as there may be overlooked competencies within a company. For example, electricians, welders, mechanics and other craftsmen were found to be working as technicians on the WTGs in our field study, and some of their basic competencies were often rarely used. When a new task is created, it is most often known which employees are able to carry out the task. Such mapping of employee's competencies and backgrounds can be carried out, as it was by the case company, through appraisal interviews and through the development of a skills matrix.

5.1.2.2 Step 2: pooling of resources. After all of the required resources have been identified, they can be divided into resource groups so that tools, spare parts, competencies and SOPs are separated. In this way, it will be easier to look for specific resources in the resource groups when required. After the pooling of the resources in this manner, the identification of these resources and their grouping into modules can begin.

5.1.2.3 Step 3: developing modules – resource packages. The modules, which we define as RPs, should be used to carry out both preventive and corrective maintenance tasks, and they should be developed based on the requirements of the various maintenance tasks. Based on studies by Hyötyläinen and Möller (2007) and our field studies, we have found that these modules must be rather small to be easily combined into larger modules, as this will allow for greater flexibility, ensuring that each module can be used for multiple tasks.

The development of RPs is the most challenging part of the modularisation process, as one must first achieve an overview of all tasks and their required resources and then look for patterns to determine which tasks may share which resources. The RPs are identified in these patterns. Figure 7 illustrates the development process of "3. Modules: Resource Packages" that are developed from "2. Resource Groups". These resource groups consist of tools (can be large or small tools, e.g. a crane, a spanner or a measuring instrument), spare parts, competences that are required (can be required, for example, by law or by management) and SOPs. Different RPs can then be used effectively to carry out different maintenance tasks.

An example of a RP could be one that includes, among other items, a specific torque wrench, specific SOPs and specific competences, which together can be used for tasks like small services, large services, the renovation of yaw-claws and the exchange of a yaw-gear.

6. Discussion

In our study of the literature on maintenance of offshore wind turbines, we found a gap on maintenance optimisation. As Utne (2010) has stated, the majority of the articles on the topic address very specific, detailed and theoretical aspects of maintenance (Sørensen, 2009). Utne (2010) further argues that there is limited information and data available to base research on. In our case study, we acquired in-depth access to company databases and interviewed both technicians and managers with several years of experience. Throughout our study, we also found the offshore wind power industry to be an immature industry which is still in rapid development. For instance, the case that we have studied was the very first offshore wind farm to be located in very rough sea conditions in the North Sea in 2002. We identified how the industry is in need of a more systematic approach to its O&M to increase efficiency and decrease costs. Therefore, we propose using Lean as a first phase of achieving these ends, followed by service modularity as a second phase. While knowledge of maintenance tasks is currently limited, we have found a bottom-up approach (Simpson *et al.*, 2001) to be appropriate for the redesign of maintenance processes.

6.1 Lean as a first step towards effective operation and maintenance

As a first step, we propose using Lean methods to reduce waste and create better flow and efficiency in the maintenance process. This will systematise operations, which, in turn, seems to speed up the processes and increase efficiency. In our study, we identified that waiting times and travelling between tasks constituted substantial waste in the maintenance process. By eliminating such waste, the case company was able to improve the performance of its assets. The case company reduced scheduled maintenance by 25 per cent, increased availability by nearly 2 per cent, increased the quality of maintenance through a one-third reduction in alarms and reduced its required personnel, which in turn reduced the number of crew vessels needed by 33 per cent.

The Lean concept was developed to make external parameters in production easier to control, which also has been identified by Bilberg (2005) and Womack and Jones (1996). The environments where offshore wind farms are located cannot be regarded as stable, as constantly changing weather conditions result in constantly changing maintenance plans. Thus, we argue that Lean is insufficient and that modularity may also be required to achieve better performance.

We have not been able to identify other studies wherein Lean was used to reduce maintenance times in relation to WTGs. Thus, our suggestion here seems to be new to the field.

6.2 Modularisation as a second step towards efficient operation and maintenance

Service modularisation is an emerging research field wherein gaps currently exist, and no common definition of the concept has been accepted (Bask *et al.*, 2011). The purpose of this paper has not been to define this concept but to try to apply service modularity to a new setting, such as the maintenance of offshore wind power installations.

In general, modularity has been discussed in terms of customising product offerings, which has been emphasised in the early works of Starr (1965). In the production of goods, it makes sense to modularise components to offer customised products to a range of different customers via limited production processes. In this study, we found that similar benefits can be achieved in relation to the maintenance of offshore WTGs, as failures often occur randomly and stochastically. As failures differ from time to time, customisation is required to correct them.

In our study, corrective failures and even predictable failures were found to create significant challenges, as the optimal weather-window is rather small in the offshore context. The weather issues decrease accessibility to the WTGs making it impossible at times – sometimes even for weeks – to visit the turbines. As the weather has a large influence on the maintenance of the WTGs, the company has to customise its services on a day-to-day basis, often even on an hourly basis. To solve this issue of varying tasks in a constantly changing environment, our study therefore suggests that modularity should be used to improve the planning and execution of O&M in the offshore wind power sector.

In our search of the literature on modularisation within maintenance and the offshore wind power industry, we were not able to identify other research with a focus on modularisation. In our development of the conceptual framework for modularising maintenance of offshore wind turbines, we identified a need for two approaches, each of which constantly influences the other, when developing the modules. The first is focusing on tasks (illustrated in Figure 5) and how they can be modularised and sequenced in a flow that is more efficient. The second is focusing on resources (illustrated in Figure 7), such as grouping modules of tools, spare parts, SOPs and competencies into RP modules.

When developing modules of tasks, we propose in this study a three-step process: the development of maintenance task modules, the identification of the required competencies for these modules and the sequencing of these modules (i.e. puzzle solving). To develop modules, one must have a good understanding of an organisation's tasks and how they relate to each other. Thus, it is crucial to involve technicians in such tasks. We have also identified that modules should be rather small to increase flexibility. In having small modules, it will be easier to re-plan and work on the modules when the puzzle is made. The modularisation process, together with Lean thinking (Bicheno, 2004; Rother and Shook, 2003), will systematise the O&M process, which may foster even better results than those obtained by the case company.

When developing resource modules, we propose a three-step process: the identification of required resources, the pooling of these resources into groups and develop modules in the form of RPs. Edvardsson *et al.* (2005) have stressed the importance of understanding the resource structure, which speaks to the importance of the first step mentioned here. To carry out maintenance tasks, it is important first to map out the necessary resources and, if some are missing, to then acquire them. By next pooling, these resources into planned groups, an organisation will be ready when new tasks arise that require specific resources by looking in its resource bank. From our field study, we observed how this process can be improved by rather small advancements. For instance, it was easier to pack the required resources for maintenance tasks, and as a result, spare parts were less likely to be forgotten.

Measuring the results of the modularisation process is necessary to confirm its success. All of the suggestions in this study are based on interviews, observations and data surveys and not on the actual testing of theories. From our empirical study, we observed how the company's Lean project reduced its required resources while increasing the quality of the work performed. However, based on the current research, it is not possible to estimate what the exact results of a modularisation process will be. To illustrate and to measure improvements and to benchmark between other offshore wind farms in a modularisation process, we therefore suggest that future studies use key performance indicators (KPIs) to analyse the benefits of an implementation of the modularisation process. Some of the KPIs listed below are already being used by the company. We have added extra KPIs which we identified through our study to be necessary to measure and benchmark improvements within such modularisation projects:

- time used for preparing (e.g. packing, planning) – not used today;
- start times of actual maintenance work (e.g. craning of equipment can delay these times) – not used today;
- total time used for scheduled services – used today; and
- number of alarms (number of failures would be preferred, but this would require a new system for the case company, which would make it impossible to compare the new situation with the past) – used today.

6.3 Contribution

This paper contributes to the field of maintenance in two areas: the topics of service modularisation and maintenance and) the improvement of maintenance in offshore wind farms. We identified two gaps in the literature: the first with regard to service modularity, which Carlborg and Kindström (2014) have noted as a gap in the literature, and the second with regard to research on maintenance optimisation within offshore wind farms, as the current research has concentrated solely on very specific and detailed theoretical aspects of maintenance (Utne, 2010). We have offered a structured two-step approach to make maintenance more efficient, whereby Lean principles should first be used to reduce waste and increase efficiency in O&M. Lean and maintenance are not newly related to each other, as Lean includes important maintenance aspects from TPM. However, when searching the literature for Lean principles used in relation to WTGs and maintenance, we were not able to identify research in this regard. This may be because the industry is still immature and has gone through heavy development, leaving little room for the improvement of various operation management theories, such as Lean. Another more likely reason for this could be that the industry is not keen on allowing access to researchers, which reduces the amount of available data and information on the topic (Utne, 2010). As we have shown substantial performance improvements due to the use of Lean in relation to the O&M of an offshore wind farm, we have helped narrow these gaps in the literature.

The second step of the suggested approach to maintenance optimisation is using modularisation theory, which represents the main contribution of our study. Based on our empirically based study, we have suggested how to implement service modularisation for the maintenance of offshore wind turbines. It is important to note that with this second step further research is required to test this theory on a larger scale. Second, we are offering empirically grounded research that focuses not on a specific and detailed part of the WTGs but on the operational level, where many different processes and actions take place. This is exactly what Utne (2010) argued was missing. Thus, our suggested two-step process supports the notion of using Lean for the O&M of offshore wind farms and contributes to the research on service modularisation.

7. Conclusion

We set out to explore how maintenance tasks can be planned in a smarter way, and consequently, how the O&M of offshore wind power installations can be improved via Lean techniques and modularisation. Our study has illustrated how a Lean approach can be used as an initial step to reduce waste and create flow in the maintenance process. A Lean approach serves to systematise operations, which speeds up processes and, in turn, increases efficiency.

In this study, we identified the ways in which the modularisation of resources and maintenance tasks can be developed to reduce time spend on maintenance. To modularise maintenance in a structured way, we developed a conceptual framework together with a suggested approach for how to implement modules of RPs. The study reveals how a modularisation process, together with SOPs, can reduce errors made during maintenance work, which in turn can increase the quality of the performed maintenance.

Maintenance planning has also been revealed to be improved by modularisation. First, it is easy to miss required resources when this information is spread among the technicians. By making such knowledge explicit, it is easier to achieve an overview of required resources. As there is a strong need to consistently reschedule maintenance work due to constantly changing weather conditions, modularisation serves to aid in this constant re-planning process. The outsourcing of tasks was also identified to become easier to handle due to the modularisation process.

This study focused on the world's first large-scale offshore wind farm, which was erected in 2002. Since then, a number of innovations and development efforts have taken place. However, research into O&M optimisation and efficiency improvement is still in its early phases in the offshore wind power industry. With the present research paper, we have contributed to the above area by investigating how modularisation of maintenance within offshore wind farms can help reduce the time spent on maintenance. In turn, this information will aid in the process of reducing the O&M costs of offshore wind turbines. The actual outcome of a modularisation process, however, must be left to future research. Such studies could include other case studies, but we would suggest also using the action research approach to test the concept of modularisation.

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