Quantifying the impact of early-stage maintenance clustering

Julie Krogh Agergaard, Kristoffer Vandrup Sigsgaard,
Niels Henrik Mortensen, Jingrui Ge and Kasper Barslund Hansen
Department of Mechanical Engineering, Technical University of Denmark, Lyngby, Denmark

Received 13 July 2021
Revised 3 December 2021
Accepted 21 March 2022

Abstract

Purpose – The purpose of this paper is to investigate the impact of early-stage maintenance clustering. Few researchers have previously studied early-stage maintenance clustering. Experience from product and service development has shown that early stages are critical to the development process, as most decisions are made during these stages. Similarly, most maintenance decisions are made during the early stages of maintenance development. Developing maintenance for clustering is expected to increase the potential of clustering.

Design/methodology/approach – A literature study and three case studies using the same data set were performed. The case studies simulate three stages of maintenance development by clustering based on the changes available at each given stage.

Findings – The study indicates an increased impact of maintenance clustering when clustering already in the first maintenance development stage. By performing clustering during the identification phase, 4.6% of the planned work hours can be saved. When clustering is done in the planning phase, 2.7% of the planned work hours can be saved. When planning is done in the scheduling phase, 2.4% of the planned work hours can be saved. The major difference in potential from the identification to the scheduling phase came from avoiding duplicate, unnecessary and erroneous work.

Originality/value – The findings from this study indicate a need for more studies on early-stage maintenance clustering, as few others have studied this.

Keywords Knowledge management, Productivity, Maintenance process, Maintenance performance, Maintenance cost management

Paper type Research paper

1. Introduction

Developing and executing optimal maintenance is an important cost and safety factor in major continuous production facilities. A failure of the equipment can be damaging to production, employees, and the environment. However, maintenance can be expensive, creating the need for a balancing act between cost efficiency and safety issues. Clustering actions during the development of maintenance jobs can help alleviate some of the maintenance costs (Van *et al.*, 2013). These can include sharing support actions such as scaffolding or minimizing production shutdowns by clustering shutdown jobs. In order to cluster for factors like these, knowledge on the maintenance situation is necessary (Assaf and Shanthikumar, 1987; Dekker *et al.*, 1997b; Hu and Zhang, 2014; Li *et al.*, 2018; Nzukam *et al.*, 2017; Van *et al.*, 2013). It can be difficult to identify potential clustering, e.g. when it is not clear whether a job requires a scaffold or how close two pieces of equipment are. The knowledge

Funding: The authors of this paper acknowledge the funding received from the Danish Offshore Technology Centre.

requirement generally makes it difficult to cluster prior to the scheduling of a job when all details but the specific date have been outlined. In the development of a maintenance job, the majority of the choices are made during the early stages. If choices about clustering were made throughout the development of the maintenance job, the job could be developed to be more compatible with other upcoming maintenance. The study presented in this paper seeks to investigate the following research question:

How does earlier clustering impact the effectiveness potential of the maintenance work?

The work effectiveness potential is defined as the amount of resources spent on achieving the same maintenance output. The research question is explored through an examination of state-of-the-art literature and three case studies. The studies evaluate clustering throughout the maintenance development phases using a data set of 916 maintenance jobs from a case company operating a large offshore asset. Each case study evaluates the clustering potential on the same dataset based on the opportunities available for change at each given stage of the maintenance development process.

2. Research method

The research question was explored through a literature study and three case studies. The literature study was focused on identifying methods and frameworks for maintenance clustering and specifically on studies that mention the relation to the maintenance management process or the required knowledge and opportunities for change within the proposed method. Information on the required knowledge and opportunities for change made it possible to place the method within the maintenance management process. The study was conducted mainly using the Technical University of Denmark (DTU) database, DTU FindIt, as well as Web of Science.

The case studies were performed at a company that operates large, continuous offshore production plants. The case studies were used to provide insight into the opportunities for clustering based on actual maintenance jobs. The studies are the basis for theory testing, as they evaluate the work effectiveness potential of the 916 maintenance jobs in the dataset (Voss *et al.*, 2016). The studies were all performed on the same dataset to enable the comparison of the results. An understanding of the maintenance management process at the case company was gained through a series of semi-structured interviews as well as the company's best practices documentation.

3. Maintenance clustering and the maintenance management process

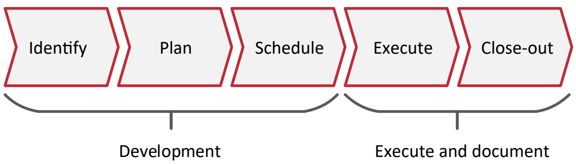
Maintenance clustering is not a novel approach in maintenance research. The body of maintenance clustering literature includes many methods, from simple block replacement to predictive, sensor-based opportunistic maintenance. This section introduces maintenance clustering as presented in the literature and determines the phase in which the proposed methods operate. Maintenance clustering methods can be split into two categories: rolling horizon and infinite horizon (Do *et al.*, 2015; Nowakowski and Werbińka, 2009; Vu *et al.*, 2016). The infinite horizon methods focus on a set interval for maintenance grouping where the maintenance intervals are performed again and again infinitely (Do *et al.*, 2015; Nowakowski and Werbińka, 2009; Vu *et al.*, 2016). This includes methods, such as block replacement, where a replacement of a group of equipment takes place after a predefined amount of time, or other methods derived from a similar process (Assaf and Shanthikumar, 1987; Sheu and Jhang, 1997). However, as production facilities are rarely static in nature, rolling horizon methods have been introduced (Dekker *et al.*, 1997b; Do *et al.*, 2015; Nowakowski and Werbińka, 2009; Van *et al.*, 2013; Vu *et al.*, 2016). Rolling horizon methods take in maintenance information within a given time horizon and clusters within this horizon (Do *et al.*, 2015; Nowakowski and

Werbińka, 2009; Vu *et al.*, 2016). Methods such as opportunistic maintenance and other methods derived from opportunistic maintenance take any failure and need for corrective maintenance as an opportunity to perform other maintenance at the same time. The methods vary based on how the decision to perform other maintenance is made (Ab-Samat and Kamaruddin, 2014; Cui and Li, 2006; Hu and Zhang, 2014; Poppe *et al.*, 2018; Wildeman *et al.*, 1997; Zhang *et al.*, 2017). Some rolling horizon methods are based on infinite horizon methods but include a dynamic component: Van *et al.* (2013), Vu *et al.* (2018), and Wu *et al.* (2020) propose similar methods that determine the optimal maintenance on an individual component level and then cluster based on different types of information, such as failure within a group or changes to the individual plans. Others have introduced methods where groups of equipment are predetermined. If one piece of equipment fails, the whole group is block replaced (Barron, 2018; Sculli and Wu, 1981).

The maintenance management process is the process through which maintenance is identified, planned, scheduled, executed, and closed-out (Figure 1). Few of the maintenance clustering methods highlighted in the previous paragraph have been discussed in relation to the maintenance management process. Generally, maintenance studies tend to focus on parts of the process and less on the full overview of the maintenance management process (Sigsgaard *et al.*, 2020). The identification phase of the process focuses on identifying and describing the need for maintenance. During this phase, the "what" of the maintenance is determined. In the planning phase, details, such as specific operations, resource requirements, skill requirements, planned time, and general date window, are determined. During this stage, the "how" of the maintenance is determined. The scheduling phase focuses on placing the orders within a given timeframe without overbooking the available employee capacity. Scheduling focuses on the "when" of the maintenance. In the execution phase, maintenance is carried out. During the close-out phase, findings and changes are documented, and financial matters are settled (Sigsgaard *et al.*, 2020). The first three phases of the process are the developmental stages, while the final two focus on the execution and documentation of the maintenance (Figure 1).

The clustering principles proposed in the studied literature are focused on the developmental stages. Table 1 shows an evaluation of the maintenance clustering methods proposed in the literature. For each method, an "X" to the right indicates the development phase in which clustering is performed. The placement of the method within the development phases is based on the required level of detail of the maintenance jobs and the choices made about the maintenance when using the method. As an example, in the method described by Sheu and Jhang (1997), the action to be taken (i.e. replacement) is predefined, and the method focuses on determining the time T at which the action should happen. Hence, it is a maintenance clustering method that focuses on the scheduling phase, deciding "when" the maintenance should happen.

As can be seen from Table 1, the majority of clustering methods focus their efforts after the specifics of the maintenance job have been determined and only the "when" remains to be decided. The method proposed by Liang and Parlikad (2020) is the only method found in the



Source(s): Figure adapted from Sigsgaard *et al.* (2020)

Figure 1.
The steps of the maintenance management process

References	Method short description	Identify "what"	Plan "how"	Schedule "when"
Liang and Parlikad (2020)	Clustering CM with possible upcoming maintenance based on predictive data	X		
Wakiru *et al.* (2018)	Clustering equipment with shared characteristics and using this data when planning the maintenance		X	
Sheu and Jhang (1997)	Equipment is replaced during major failures in the first phase and left idle in the second phase until a predefined time T when all are replaced at once			X
Dekker *et al.* (1997a)	Clustering of equipment in parallel: failed equipment is left idle until the other equipment also need maintenance and are then replaced			X
Assaf and Shanthikumar (1987)	Leaving equipment failed until a certain number of parts have failed. Then, repair is done all at once			X
Sculli and Wu (1981)	When one component fails, the whole system is replaced			X
Barron (2018)	Replacement is performed every T units of time			X
Barron (2018)	After a given number of component failures, maintenance is carried out			X
Barron (2018)	Inspection is performed at given intervals unless a time T has been reached; then, everything is replaced			X
De Jonge *et al.* (2016)	Applying condition-based clustering on an asset level			X
Cui and Li (2006)	Multi-component shock model for opportunistic maintenance			X
Dekker and Smeitink (1991)	Opportunistic block replacement			X
Poppe *et al.* (2018)	Opportunistic condition-based maintenance			X
Zhang *et al.* (2017)	Opportunistic wind turbine maintenance			X
Hu and Zhang (2014)	Risk-based opportunistic maintenance			X
Wildeman *et al.* (1997)	Rolling horizon grouping method based on the PM plan			X
Vu *et al.* (2018)	Optimizing maintenance cycles on an individual equipment level, then grouping			X
Wu *et al.* (2020)	Determine individual threshold replacement age. Correctively replace individually prior to threshold, preventively replace in a group after threshold			X
Van *et al.* (2013)	Individual equipment maintenance optimization and tentative planning followed by grouping optimization			X
Nzukam *et al.* (2017)	Dynamic grouping in scheduling based on predictive information, component criticality, and stoppage characteristics			X
Peng and Ouyang (2014)	Clustering maintenance jobs in railroad maintenance			X

(*continued*)

Table 1.
Evaluation of the placement within the maintenance development phases of the maintenance clustering methods proposed in literature

References	Method short description	Identify "what"	Plan "how"	Schedule "when"
Seif *et al.* (2020)	Clustering periodic preventive maintenance in campaigns based on shutdown requirements			X
Van Dijkhuizen and Van Harten (1997)	Clustering to improve shared setups for periodic preventive maintenance			X
Abdelhadi *et al.* (2015)	Applying group technology principles to improve maintenance costs			X
Total number of methods		1	1	22

Table 1.

literature where clustering and the "what" are decided. Liang and Parlikad (2020) propose the use of predictive data to decide whether any preventive maintenance should be performed in addition to the upcoming corrective maintenance (CM). Hence, in this method, a decision on "what" preventive maintenance (PM) to perform is made. However, the "what", "how", and "when" are already determined for the CM. The study by Wakiru *et al.* (2018), the only study identified that focuses on the planning phase, presents a method in which equipment is clustered prior to maintenance planning. The clusters are then used as an outset for clustering during maintenance planning. Table 1 shows that most of the clustering efforts presented in the literature focus on the end of the development phases. However, during developmental projects, the majority of decisions are made during the early stages (Martin *et al.*, 2007; McAloone and Bey, 2009; Saravi *et al.*, 2013; Shehab and Abdalla, 2001; Zrim *et al.*, 2006). When a development decision is made, it is typically expensive to change it. Hence, changes later in the process are difficult and expensive to make (Martin *et al.*, 2007).

4. Improving the knowledge foundation

The results from Table 1 show that the majority of the methods presented in the literature require some type of knowledge on the "what" and "how" prior to clustering. The minimum knowledge requirement for clustering is represented by the orange dashed line in Figure 2. When maintenance is developed without the application of any type of knowledge, the amount of knowledge is slowly developed throughout the maintenance management development phases (bottom, red line, Figure 2). This means that the amount of knowledge required for clustering is not available until later in the process.

In order to enable earlier clustering, the starting knowledge of the maintenance job must be increased via the introduction of a knowledge base, such as a maintenance database, that provides information about the development of the maintenance job. The knowledge can include dynamic information about upcoming maintenance as well as historical knowledge that can illustrate the solution options for the maintenance job. The improvement of the knowledge base will make it possible for clustering decisions to be made much earlier in the process (top, green line, Figure 2). As a majority of decisions are made during early development, the earlier the clustering decision is made, the bigger the opportunity for change in the maintenance job. When these decisions are made earlier in the process, the maintenance can be developed for clustering.

5. Case studies and main findings

To evaluate the clustering optimization potential from clustering during the different development phases, three case studies were performed at a company that operates major offshore assets. The case studies illustrate the effect of the use of data for clustering at different stages of the maintenance management process. The company operates 50 offshore platforms that consist of hundreds of thousands of pieces of maintainable equipment. Across the plants, an average of about 24,000 man hours was spent on maintenance jobs per week in 2018. Each time a maintenance job is performed, costs are incurred from the man hours spent, the use of replaced and refillable materials, production loss, accommodation, employee transportation, and more. Cost optimization is countered by the urgent need for safety on plants far from shore that operate at large pressures with flammable mediums. In order to balance these goals, there is a need for maintenance optimization that does not rely on changing the maintenance tool time, thus not affecting the equipment reliability. This makes clustering an interesting area to explore, as the focus is on sharing supporting actions and avoiding unnecessary and duplicate maintenance.

5.1 Preparing the maintenance job data

The case studies were preceded by the standardization of the maintenance job data from the company's computerized maintenance management system (CMMS). The focus of building the database and business intelligence (BI) dashboards was on understanding the overlaps in variance and eliminating non-value-adding variation. Non-value-adding variation will make it seem like clustering is not an option when there is a clustering opportunity. A lot of the data was already standardized due to the structure of the CMMS. The largest amount of variation was found in the operations that described the actions to take during the maintenance job.

By analyzing the variants of words within the operations, it was clear that only a few variants were value-adding. The words from all operations were extracted from the maintenance job data. All words that describe the action taken in a job were then extracted. These included words such as isolate, replace, and clean. Words, such as on, behind, and pump, were excluded, as they did not describe the action taken. All non-value-adding variants were then grouped under shared action words, and only the shared action word was used. A similar process was performed for the targets of the action words. A target of an action word, such as isolate, can be equipment, area, or system, and the target of a replace action can include elements, such as a component, equipment, or medium.

Most task clusters require the equipment being maintained to be close together. In large offshore production plants, it can be difficult to know the distance between tagged locations

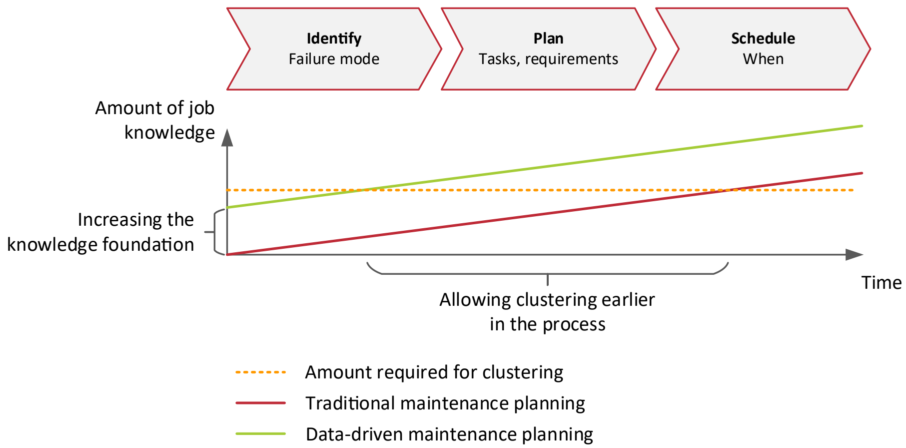


Figure 2. The amount of knowledge about a job is increased throughout the maintenance management process. Clustering will typically require some type of knowledge minimum. By supplying the maintenance management process with data, the knowledge foundation is lifted, making clustering possible earlier

from onshore. At the case company, the relation between the pieces of equipment was documented using piping and instrumentation diagrams (P&IDs) and a location hierarchy implemented in the CMMS. Figure 3 shows a simplified example of a P&ID. Each piece of equipment has a number of connected or adjacent pieces of equipment. Each piece of equipment can also be broken down into its constituent components. For example, a pump consists of components, such as coupling, connections, and seals and is part of a pumping package that is connected to the production flow. Using the location hierarchy from the database, it was possible to select relevant locations for the clustering.

By linking the data on the physical proximity of the equipment to the maintenance jobs, it was possible to identify maintenance on parts of packages and groups of close equipment. The structured historical database was then linked to a scope of open orders from an area of the offshore asset. The scope included 916 orders across six connected plants, all waiting to be scheduled. The scope was applied in all three clustering case studies.

5.2 Case study I: clustering during scheduling

This case study illustrates opportunities for clustering during the scheduling phase. In the case company, jobs planned for the upcoming two weeks are scheduled by a group of expert schedulers. They receive information about the jobs, including the number and description of the operations, the planned timeframes for these operations, and the required employee capacity and skills. Each job must be placed within the predefined timeframe based on the earliest and latest allowed dates. The main goal of the scheduling process is to postpone as few jobs as possible while using up the available employee capacity. Table 2 shows an excerpt from the table used by a scheduler.

The clustering was focused on improving the number of shared support actions by utilizing the standardized maintenance operation actions. By reading and understanding the operations shown in the excerpt in Table 2, one can manually identify groups. However, on a larger scale, with about 1,000 jobs that need to be scheduled every 14 days, it is impossible to read every operation line in order to identify commonalities. The use of standardized operations can simplify the cluster identification process. The standardized versions of the operations from the sample excerpt are shown in Table 3.

A simple formula in an Excel table was able to flag similarities across the orders using the standardized operations. In the sample orders in Table 3, two types of clusters were identified. The first cluster includes jobs A and B that are on a pump and the corresponding pump motor. These two functional locations are within the same area, and both require the isolation

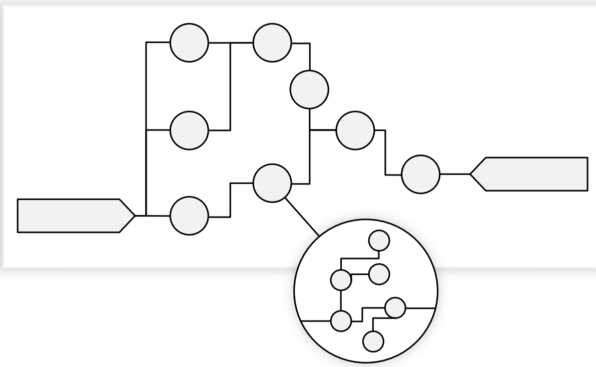


Figure 3.
Cut-out representation of the production flow. A piece of equipment is connected to several others. It can also be broken down into its individual constituent components

of the area. Scheduling the isolation and de-isolation operations of these jobs on the same day would result in only having to isolate and de-isolate the area once instead of twice. This would mean that four man hours could be saved, reducing the amount of time spent at the location. Similarly, clustering the scaffolding on area B for jobs C and D would eliminate the need to take down the scaffold between jobs. As scaffolding is a time-consuming task, this could save 18 man hours. Based on the simple sample orders from Table 3, this means 31% of the planned hours and 21% of the planned operations can be saved. This simple flagging of orders was implemented for all 916 open orders in the scope. By clustering orders that shared isolations and scaffolding, an estimated 2.4% of work hours could be saved, and 4.6% of the number of operations eliminated.

Table 2.
Excerpt of the As-Is format of maintenance jobs used in scheduling. Some columns, such as dates, material requirements, and drop-off points, are excluded from this excerpt

Order	Location	Equipment Type	Activity Number	Operation	Skills	Employees [#]	Planned work [h]
A	A.1	Pump	1	Isolate pump from production	Production	2	2
			2	Remove current pump A.1 and replace with new pump XBPU1895	Mechanics	1	5
			3	De-Isolate	Production	2	2
			4	Do test of new pump	Mechanics	1	1
			5	Document pump replacement in master data	Mechanics	1	1
B	A.2	Pump motor	1	Safe pump + motor	Production	2	2
			2	Do Function Test of motor	Mechanics	1	3
			3	De-safe motor + pump	Production	2	2
			4	Document test results in master data	Mechanics	1	1
C	B.1	Emergency Valve	1	Erect scaffold to reach valve	Scaf-team	2	12
			2	Isolate	Production	2	2
			3	Clean up the valve	Mechanics	1	3
			4	De-Isolate	Production	2	2
			5	Remove scaffold	Scaf-team	2	6
			6	Document maintenance	Mechanics	1	1
D	B.2	Vessel	1	Build scaffold	Scaf-team	2	12
			2	Function Test of the vessel	Mechanics	1	8
			3	Document	Mechanics	1	1
			4	Take down the scaff	Scaf-team	2	6

Table 3.
Marking the shared actions on nearby equipment. Clustering by shared actions means only performing the shared action once and then doing all the maintenance

Order	Location	Equipment Type	Activity Number	Operation action	Operation target	Skills	Employees [#]	Planned work [h]
A	A.1	Pump	1	Isolate	Area	Production	2	2
			2	Replace	Pump	Mechanics	1	5
			3	De-Isolate	Area	Production	2	2
			4	Test	Pump	Mechanics	1	1
			5	Document	Pump	Mechanics	1	1
B	A.2	Pump motor	1	Isolate	Area	Production	2	2
			2	Function Test	Pump motor	Mechanics	1	3
			3	De-Isolate	Area	Production	2	2
			4	Document	Pump motor	Mechanics	1	1
C	B.1	Emergency Valve	1	Erect scaffold	Area	Scaf-team	2	12
			2	Isolate	Area	Production	2	2
			3	Clean	Emergency Valve	Mechanics	1	3
			4	De-Isolate	Area	Production	2	2
			5	Take down scaffold	Area	Scaf-team	2	6
			6	Document	Emergency Valve	Mechanics	1	1
D	B.2	Vessel	1	Erect scaffold	Area	Scaf-team	2	12
			2	Function Test	Vessel	Mechanics	1	8
			3	Document	Vessel	Mechanics	1	1
			4	Take down scaffold	Area	Scaf-team	2	6

Note(s): Isolation clustering Scaffold clustering

5.3 Case study II: clustering during planning

This case study illustrates opportunities for clustering during the planning phase. When jobs are clustered in the planning phase, it is possible to include clustering considerations when deciding the actions taken in the jobs. At the case company, only CM is dynamically planned. PM is planned once and set to be automatically released for scheduling at predetermined intervals. PM jobs are typically released 120 days prior to their execution, making them active in the system during the planning of many CM jobs.

CM jobs are planned based on notifications that point to a need for maintenance. The notifications are made by offshore personnel. The maintenance planner plans the job based on aspects such as the type, criticality, and location of the failure. Planning a job includes determining details such as operations, materials, number of employees, employee skills, and amount of hours required to complete the job. Currently, the only sources of knowledge the maintenance planner has for planning are the notification, their own experience, and a collection of documentation spread out in various digital and physical locations. This leads to maintenance jobs that are planned independently with a disregard for contextual factors, such as shared support actions and other upcoming maintenance. When the maintenance planner has information about other relevant upcoming maintenance, they are able to cluster the job currently being planned with other upcoming maintenance.

The case study focused on the scope of 916 orders. In the study, the operations within the orders could be changed; however, only the newest orders could be planned to suit upcoming maintenance that had already been released. Using the original dates from the maintenance jobs, it was possible to identify which orders were planned first. At this stage, only the CM jobs that are added later can be edited to fit other upcoming maintenance. As PM jobs are automatically released 180 days prior to their execution, they cannot be changed. However, CM jobs planned within 180 days can be clustered with the PM jobs (Figure 4, Top). CM jobs were also clustered with other upcoming CM jobs when relevant (Figure 4, Bottom).

The relevance of upcoming maintenance was based on location and an overlap of actions. If an upcoming job was a duplicate of the more recent job, only one was kept. If a preventive replacement was coming up, no CM was planned. The jobs were also planned to share support actions, such as isolation/de-isolation and scaffolding. By performing the clustering on the CM jobs in the open order case study, 2.7% of the planned hours could be saved, and 5.9% of the number of operations could be eliminated.

5.4 Case study III: clustering during identification

This case study illustrates opportunities for clustering in the identification stage. During the identification stage, the case company identifies the need for maintenance. This is the stage where the offshore employees notify onshore personnel of a failure. The failure is notified using information, such as location, severity, failure mode, and observation type, along with a free text description of the failure. At the case company, a failure is when a piece of equipment is no longer performing its function correctly. This can involve anything from a slower or less smooth movement of a backup part to critical failures that shut down production or pose a safety danger. The first action taken when a failure is notified is a decision on the general solution to the failure. This case study focused on upcoming maintenance when deciding on the solution. When the upcoming maintenance is known, the notified job can be clustered with that maintenance before the job is planned. As an example, say a valve is leaking in the connection to the pipe because a seal has been worn out and is due to be replaced within the following month. From the upcoming maintenance data, the maintenance planner can see that the whole valve is set to be preventively replaced in about a month. The planner will then know whether this entails a replacement of the seal or will then be able to add a seal replacement action to the upcoming PM job, entirely avoiding the planning of a new job. Such

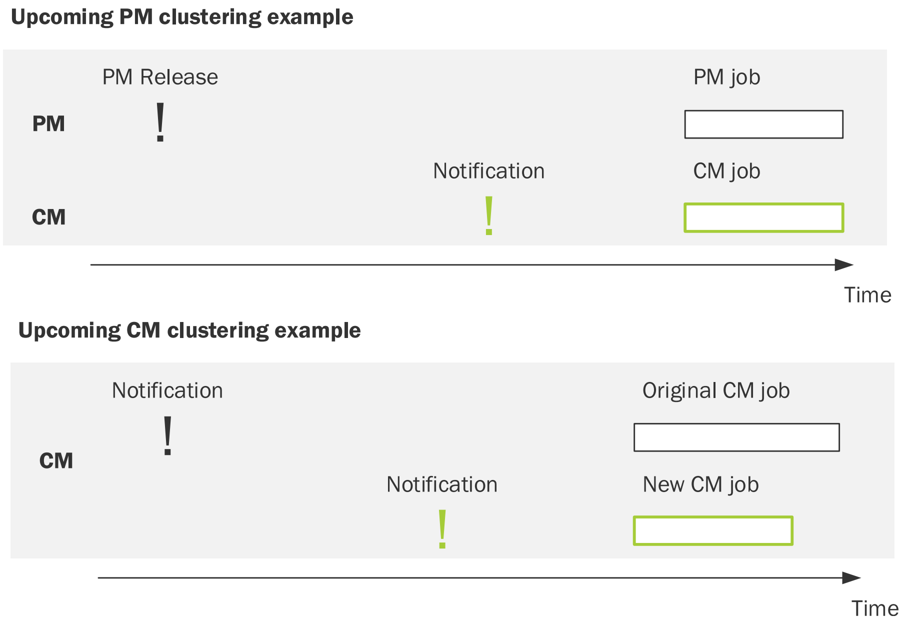


Figure 4.
Examples of clustering in planning. A green outline indicates the newer job. Top: A CM job is planned alongside an upcoming PM job. Bottom: The new CM job is clustered with an already planned CM job

efforts will similarly help avoid duplicate jobs due to backlogged items, the planning of incompatible jobs, or unnecessary life-prolonging actions prior to a replacement.

Figure 5 shows two examples of identification clustering performed in the case study. The top graph shows an example where a valve connection seal failed prior to a preventive replacement. In this scenario, a seal failure was notified after the release of a valve replacement job. In the as-is process at the case company, the expert planning the maintenance action based on the notification will likely not be aware of the upcoming valve replacement job. However, these two jobs are highly compatible, and when the planner has access to data that makes them aware of the upcoming maintenance, they can add the seal replacement action to the valve replacement job. This simplifies both the maintenance actions taken offshore as well as the planning and scheduling process onshore. The bottom graph shows an example of a valve cleaning prior to a preventive replacement. A notification was created, as issues with the open and close times were discovered on a valve. In the as-is, the maintenance planner did not notice the upcoming preventive replacement of the valve. As the replacement of the valve makes the cleaning unnecessary, the planner can instead point the notification towards the replacement as the maintenance mitigating the open-closing failure.

Applying similar evaluations to the full scope of open orders, the amount of planned maintenance hours and number of operations required to be performed was further reduced. The effort showed that 4.6% of the planned maintenance hours could be saved, and 9.2% of the operations could be eliminated. Of the 916 orders, 29 were duplicates of one or more jobs at the same location. Another eight jobs included maintenance that was unnecessary compared to the upcoming maintenance. Four jobs were planned with errors and included duplicate actions. Improvements on these 41 duplicate, unnecessary, or erroneous jobs accounted for 3.1% of the improved planned hours and 5.5% of the eliminated operations.

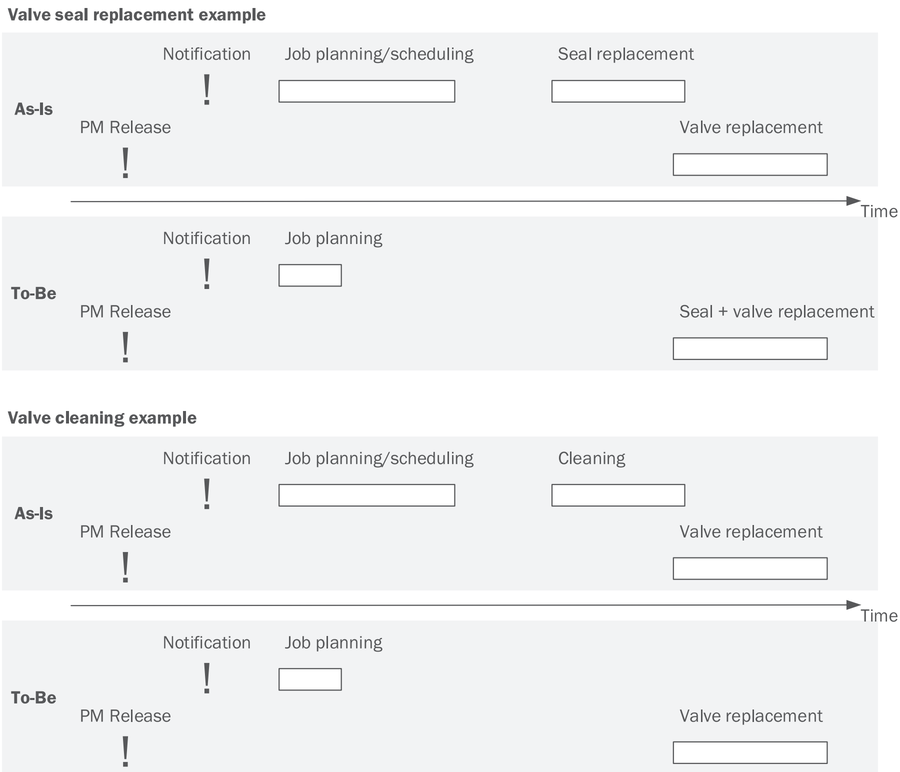


Figure 5. Clustering in the identification stage involves making the right choice about maintenance compatibility. Top: The seal replacement for the valve is combined with an upcoming preventive valve replacement. Bottom: The cleaning of a valve is unnecessary when the valve is about to be replaced

6. Discussion

The case studies show how early-stage clustering provides more opportunities for change, improving the optimization foundation (Figure 6). The study focused on the following research question:

How does earlier clustering impact the effectiveness potential of maintenance work?

The research question was explored through a systematic evaluation of methods proposed in the maintenance literature and a case study on 916 open orders from a company operating a large offshore asset. The literature study showed how most methods in the literature mention little about their relation to the maintenance management process. The requirements for and decisions made using the identified maintenance clustering methods show that the majority of the identified methods will not be possible until the scheduling of the maintenance. However, the results from the case study indicate that the changes possible in the earlier stages, especially during the identification phase, reduce both the amount of planned work hours and especially the number of planned operations that need to be scheduled and executed (Figure 6). As the minimization of the planned work hours and operations only affects support actions and unnecessary or duplicate maintenance work, the effect of the clustering is on the work efficiency and will have little to no impact on the state of the equipment.

In the scheduling phase, the least amount of change can be made, as both the “what” and “how” have been determined. Consequently, the improvement potential in this phase is the lowest out of all three case studies (Figure 6). When few changes are possible, little efficiency can be achieved without incurring extra costs to change the job.

The difference between clustering in scheduling and clustering in planning is small and mostly impacts the number of operations rather than the amount of hours spent (Figure 6). This indicates that once the choice of "what" maintenance to perform is made, the amount of changes available is limited. This is also evident in the difference between the results from the identification and planning phases (Figure 6). Changes available in planning include less impactful options, such as choosing a differently skilled person to perform the job or deciding to use the rope team instead of a scaffold and so forth.

Larger, more impactful changes were possible when clustering was done in the identification phase. These changes were largely due to the ability to combine the maintenance with other upcoming maintenance, e.g. avoiding unnecessary corrective actions right before an extensive preventive job. As concluded in the identification case study, 3.1% of the planned hours and 5.5% of the planned operations could be saved by minimizing erroneous, duplicate, and unnecessary work. Alone, this is greater than the full potential of clustering during the scheduling phase, indicating that clustering early in the maintenance development process has great potential.

As shown in Table 1, most of the methods identified in the literature focus on scheduling. This indicates a need for the exploration of methods for early stage clustering in maintenance research. Generally, the methods identified in the literature review did not consider the relation to the maintenance management process or to the data maturity required for the method. The results of this study are dependent on the availability of the data, indicating a need for more considerations on data availability in the maintenance literature.

The study indicates a rather significant difference in clustering in identification compared to scheduling. However, this study was based on emulations of the changes made. Future studies on the benefits of early stage clustering should investigate the efficacy of clustering during the identification phase in real time, i.e. when the jobs are actually being notified. Such studies would provide additional information on the type of knowledge required and the opportunities available for clustering during the early stages. Other studies investigating other scopes in both the same case company and others are also necessary to further validate the findings produced in the study presented in this paper.

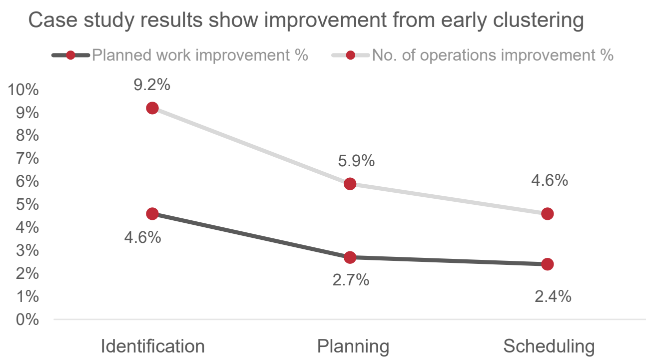


Figure 6. Resulting improvements from clustering in identification, planning, and scheduling. The case study results indicate the benefits of performing clustering as early as possible

7. Conclusion

The study presented in this paper indicates an improvement in the work efficiency potential when clustering is done in the early stages of the maintenance development process. The study showed an opportunity for eliminating 2.4% of maintenance hours when clustering is done during the last stage (scheduling) versus an opportunity for eliminating 4.6% of maintenance hours when clustering is done during the first stage (identification). The difference in the opportunities for change between the two stages mainly lies in the opportunity to avoid duplicate and unnecessary maintenance when the clustering is performed during the identification stage. Clustering during earlier stages was possible, as data describing other surrounding maintenance was available during the clustering.

References

Ab-Samat, H. and Kamaruddin, S. (2014), "Opportunistic maintenance (OM) as a new advancement in maintenance approaches: a review", *Journal of Quality in Maintenance Engineering*, Emerald Group Publishing, Vol. 20 No. 2, pp. 98-121.

Abdelhadi, A., Alwan, L.C. and Yue, X. (2015), "Managing storeroom operations using cluster-based preventative maintenance", *Journal of Quality in Maintenance Engineering*, Emerald Group Publishing, Vol. 21 No. 2, pp. 154-170.

Assaf, D. and Shanthikumar, G.J. (1987), "Optimal group maintenance policies with continuous and periodic inspections", *Management Science*, Vol. 33 No. 1, pp. 1440-1452.

Barron, Y. (2018), "Group maintenance policies for an R-out-of-N system with phase-type distribution", *Annals of Operations Research*, Springer Science and Business Media, LLC, Vol. 261 Nos 1-2, pp. 79-105.

Cui, L. and Li, H. (2006), "Opportunistic maintenance for multi-component shock models", *Mathematical Methods of Operations Research*, Vol. 63 No. 3, pp. 493-511.

De Jonge, B., Klingenberg, W., Teunter, R. and Tinga, T. (2016), "Reducing costs by clustering maintenance activities for multiple critical units", *Reliability Engineering and System Safety*, Elsevier, Vol. 145, pp. 93-103.

Dekker, R. and Smeitink, E. (1991), "Opportunity-based block replacement", *European Journal of Operational Research*, Vol. 53 No. 1, pp. 46-63.

Dekker, R., Wildeman, R.E. and Van Der Duyn Schouten, F.A. (1997a), "A review of multi-component maintenance models with economic dependence", *Mathematical Methods of Operations Research*, Physica-Verlag, Vol. 45 No. 3, pp. 411-435.

Dekker, R., Wildeman, R.E. and Schouten, F.A.V.D.D. (1997b), "A review of multi-component maintenance models with economic dependence", *Mathematical Methods of Operations Research*, Physica-Verlag, Vol. 45 No. 3, pp. 411-435.

Do, P., Vu, H.C., Barros, A. and Bérenguer, C. (2015), "Maintenance grouping for multi-component systems with availability constraints and limited maintenance teams", *Reliability Engineering and System Safety*, Elsevier, Vol. 142, pp. 56-67.

Hu, J. and Zhang, L. (2014), "Risk based opportunistic maintenance model for complex mechanical systems", *Expert Systems with Applications*, Vol. 41 No. 6, pp. 3105-3115.

Li, G., Li, Y., Zhang, X., Hou, C., He, J., Xu, B. and Chen, J. (2018), "Development of a preventive maintenance strategy for an automatic production line based on group maintenance method", *Applied Sciences (Switzerland)*, MDPI AG, Vol. 8 No. 10, doi: 10.3390/app8101781.

Liang, Z. and Parlikad, A.K. (2020), "Predictive group maintenance for multi-system multi-component networks", *Reliability Engineering and System Safety*, Elsevier, Vol. 195, doi: 10.1016/j.ress.2019.106704.

Martin, P., Dantan, J.-Y. and Siadat, A. (2007), "Cost estimation and conceptual process planning", *Digital Enterprise Technology*, Springer International Publishing, pp. 243-250.

McAloone, T.C. and Bey, N. (2009), *Environmental Improvement through Product Development - A Guide*, Danish Environmental Protection Agency.

Nowakowski, T. and Werbińka, S. (2009), "On problems of multicomponent system maintenance modelling", *International Journal of Automation and Computing*, Vol. 6 No. 4, pp. 364-378.

Nzukam, C., Voisin, A., Levrat, E., Sauter, D. and Iung, B. (2017), "A dynamic maintenance decision approach based on maintenance action grouping for HVAC maintenance costs savings in Non-residential buildings", *IFAC-PapersOnLine*, Elsevier B.V., Vol. 50 No. 1, pp. 13722-13727.

Peng, F. and Ouyang, Y. (2014), "Optimal clustering of railroad track maintenance jobs", *Computer-Aided Civil and Infrastructure Engineering*, Vol. 29 No. 4, pp. 235-247.

Poppe, J., Boute, R.N. and Lambrecht, M.R. (2018), "A hybrid condition-based maintenance policy for continuously monitored components with two degradation thresholds", *European Journal of Operational Research*, Elsevier B.V., Vol. 268 No. 2, pp. 515-532.

Saravi, M., Newnes, L. and Mileham, T. (2013), "Optimising performance and cost at the early design stages", *International Journal of Engineering and Technology Innovation*, Vol. 3 No. 3, pp. 214-228.

Sculli, D. and Wu, S.Y. (1981), "Block replacement for units whose components have weibul life distributions", *Computers and Operations Research*, Vol. 8 No. 4, pp. 295-302.

Seif, Z., Mardaneh, E., Loxton, R. and Lockwood, A. (2020), "Minimizing equipment shutdowns in oil and gas campaign maintenance", *Journal of the Operational Research Society*, Taylor and Francis, Vol. 72 No. 7, doi: 10.1080/01605682.2020.1745699.

Shehab, E.M. and Abdalla, H.S. (2001), "Manufacturing cost modelling for concurrent product development", *Robotics and Computer-Integrated Manufacturing*, Vol. 17 No. 4, pp. 341-353.

Sheu, S.H. and Jhang, J.P. (1997), "A generalized group maintenance policy", *European Journal of Operational Research*, Elsevier, Vol. 96 No. 2, pp. 232-247.

Sigsgaard, K.V., Agergaard, J.K., Mortensen, N.H., Hansen, K.B., Soleymani, I. and Khalid, W. (2020), "Initiatives towards a concurrent maintenance process", *Proceedings of Norddesign: Balancing Innovation and Operation*, The Design Society, doi: 10.35199/NORDDESIGN2020.23.

Van Dijkhuizen, G. and Van Harten, A. (1997), "Optimal clustering of frequency-constrained maintenance jobs with shared set-ups", *European Journal of Operational Research*, Elsevier, Vol. 99 No. 3, pp. 552-564.

Van, P. Do, Barros, A., Bérenguer, C., Bouvard, K. and Brissaud, F. (2013), "Dynamic grouping maintenance with time limited opportunities", *Reliability Engineering and System Safety*, Elsevier, Vol. 120, pp. 51-59.

Voss, C., Johnson, M. and Godsell, J. (2016), *"Case Research", Research Methods for Operations Management*, 2nd ed., Routledge, pp. 181-213.

Vu, H.C., Do, P. and Barros, A. (2016), "A stationary grouping maintenance strategy using mean residual life and the birnbaum importance measure for complex structures", *IEEE Transactions on Reliability*, Institute of Electrical and Electronics Engineers, Vol. 65 No. 1, pp. 217-234.

Vu, H.C., Do, P. and Barros, A. (2018), "A study on the impacts of maintenance duration on dynamic grouping modeling and optimization of multicomponent systems", *IEEE Transactions on Reliability*, Institute of Electrical and Electronics Engineers, Vol. 67 No. 3, pp. 1377-1392.

Wakiru, J.M., Pintelon, L., Karanović, V.V., Jocanović, M.T. and Orošnjak, M.D. (2018), "Analysis of lubrication oil towards maintenance grouping for multiple equipment using fuzzy cluster analysis", *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Vol. 393, doi: 10.1088/1757-899X/393/1/012011.

Wildeman, R.E., Dekker, R. and Smit, A.C.J.M. (1997), "A dynamic policy for grouping maintenance activities", *European Journal of Operational Research*, Elsevier, Vol. 99 No. 3, pp. 530-551.

Wu, T., Yang, L., Ma, X., Zhang, Z. and Zhao, Y. (2020), "Dynamic maintenance strategy with iteratively updated group information", *Reliability Engineering and System Safety*, Elsevier, Vol. 197, doi: 10.1016/j.ress.2020.106820.

Zhang, C., Gao, W., Guo, S., Li, Y. and Yang, T. (2017), "Opportunistic maintenance for wind turbines considering imperfect, reliability-based maintenance", *Renewable Energy*, Elsevier, Vol. 103, pp. 606-612.

Zrim, G., Maletz, M. and Lossack, R. (2006), "Experience based cost management in the early stages of product development", *9th International Design Conference, DESIGN 2006*, pp. 1569-1574.

Corresponding author
Julie Krogh Agergaard can be contacted at: jkrag@mek.dtu.dk