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Towards cleaner and more productive maintenance in petrochemical facilities: Mechanization and an assessment method

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ABSTRACT

Maintenance in petrochemical plants is often characterized as labor intensive and may give rise to such problems as being costly, diminishing productivity, and emitting pollutant. To mitigate such problems, managers have tried mechanizing the maintenance tasks. This study elaborated the concept of mechanization, proposed a method named Petrochemical Maintenance Mechanization Assessment (PEMMA), which can help assess mechanization levels of the maintenance tasks and provide corresponding improvement recommendations This study presented the development process of the PEMMA method and applied the method in the context of Singapore. Results showed that the mechanization level of the maintenance tasks in Singapore is relatively low. The developed method is arguably the first to be presented and therefore, it contributes to the existing body of knowledge. In addition, the developed method is beneficial to the practice as well, because it can help diagnose and then improve the mechanization levels of petrochemical plants, which would eventually make the petrochemical industry more productive and cleaner.

1. Introduction

One of the most important industries to most nations is the petrochemical industry, as this industry is responsible for creating many products that are essential to modern life—plastics, cosmetics, paints and lubricants (Ruqaishi and Bashir, 2015). A crucial component of petrochemical plants running efficiently is that of maintenance. Indeed, various types of equipment occasionally break down from wear and tear, aging, inefficient processes, failure, and human error. Recent news has shown, however, maintenance in petrochemical facilities is confronted with an issue of low productivity thanks to the extensive use of labor forces (Loera-Hernández and Espinosa-Garza, 2014). Apart from that, maintenance in petrochemical facilities could discharge large amount of pollutants (e.g., wastewater and solid waste) which are difficult to deal with artificially (Wen et al., 2019).

Plant managers have tried numerous ways to address these issues, including mechanization. According to Willis (1875), mechanization refers to the process of change, from working largely or exclusively by hand or with animals to working with hand-tools or powered equipment. It enables people to quickly handle an otherwise overwhelming workload. Therefore, it can increase the efficiency and productivity of the production activities significantly. Adopting mechanization in maintaining petrochemical facilities have clear benefits. Doing so can reduce work duration, enhance work quality and precision, and circumvent the shortage of skilled labor in some specific types of work (Sawyer, 2016). It can also increase workplace safety, as the use of mechanized tools and equipment can eliminate potential hazards to be faced by frontline workers (Iversen and Geehan, 2015). Moreover, it can help create a clean and hygienic environment which would be beneficial to the workers onsite (Yin et al., 2019). It is evident that the higher the mechanization level is, the more productive and cleaner the maintenance tasks will be. Therefore, it is necessary for industry practitioners to know the mechanization level of the maintenance tasks carried out in their plants.

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Assessing mechanization levels has been the subject of several studies. Sharabiani and Ranjbar (2008) assessed the level of the agricultural mechanization in Sarab Region. Jalalzadeh et al. (2016) assessed the mechanization level of crop production in Iran. Turker et al. (2011) assessed the agricultural mechanization levels in the Southeastern Anatolia Region in Turkey. Mccormack et al. (2012) assessed the levels of farm mechanization. Zangeneh et al. (2010) and Zangeneh et al. (2015) assessed the mechanization levels of the potato farms in Iran. Mehdi et al. (2013) proposed a method that could assess the mechanization levels of the coal-mining process. However, most of these studies concerned the assessment in the fields of agriculture and mining. The petrochemical industry still lacks a method that assesses mechanization levels. The motivation of this study is to develop a standardized method that can help industry practitioners assess the mechanization levels of maintenance tasks and provide practitioners with resources for mechanization improvement. This study can contribute to the current body of knowledge of mechanization by adding to the literature of mechanization assessment in the petrochemical industry. In addition, the present study is useful to the practice as well, because it can provide industry practitioners with a practical approach to assess the mechanization levels of the maintenance tasks carried out in their plants.

2. Literature review

2.1. Maintenance tasks in petrochemical facilities and mechanization

According to the Cambridge Dictionary (2018), maintenance refers to “the activity of keeping a building, vehicle, road, etc. in good condition by checking it regularly and repairing it when necessary.” Moubray (1997) provided a definition that is more academic. He defined maintenance as “the combination of all technical, administrative and managerial actions carried out during the life of an item intended to retain it in, or restore it to, a state in which it can perform its required function.” As asserted both by Arts et al. (1998) and Hajej et al. (2015), maintenance plays a supporting role to the production process that transforms raw materials into final products, with the main objective of keeping the process running and maximizing the availability of production. For petrochemical facilities, typical maintenance tasks include cleaning, inspecting, lubricating, testing, replacing, and/or repairing (Veldman et al., 2011). These tasks are performed on different facilities in petrochemical plants such as tanks, heat exchangers, furnaces, towers, fin fans, and reactors. Maintenance tasks in the petrochemical industry have one unique characteristic—they are more vulnerable to risks and are more likely to be on the critical path of the production schedule (Guiras et al., 2019). In other words, maintenance is crucial to the petrochemical industry. Therefore, it is vital to reduce the durations of the maintenance tasks carried out in petrochemical facilities, minimizing the disruption and making sure that production resumes as quickly as possible.

The duration of the maintenance tasks can be reduced by using mechanized tools and equipment and therefore, in petrochemical facilities, maintenance departments use a wide range of these (Richardson, 2013). To clean sludge from tanks, for example, maintenance personnel use vacuum trucks and hydraulic slush dozers (Wen et al., 2019); to re-surface the face of the exchanger flange, some personnel use milling machines (Praveen et al., 2019). Drones are increasingly used to inspect and identify repairs needed for fin fan (Nižetić et al., 2019); borescopes have been used to inspect furnaces (Simpson et al., 2018); pressure jets have been used to clean reactors (Ha et al., 2019); pneumatic angle grinders have been used to cut piping (Wills and Finch, 2015); portable drills have been used to drill inspection holes through insulation to inspect the possible corrosion of metal (Mannan, 2012). Despite this variety of mechanization, there is still no method to assess the levels of mechanization of maintenance tasks. In response to this lack, the current study has developed the Petrochemical Maintenance Mechanization Assessment (PEMMA), a method that can help industry practitioners assess the levels of mechanization in their maintenance tasks.

2.2. Mechanization assessment

It is important for a company to assess its mechanization levels. The company will discover how mechanized its implementation activities are and to what degree they can be improved. Other fields (e.g., agriculture and mining) have produced several studies examining the assessment of mechanization. By calculating how much tractor power was used per cultivated area, Sharabiani and Ranjbar (2008) assessed the level of the agricultural mechanization in Sarab Region. Jalalzadeh et al. (2016) used a similar method to assess the mechanization level of crop production in Iran. To assess agricultural mechanization levels in the Southeastern Anatolia Region in Turkey, Turker et al. (2011) proposed the following four indicators: the tractor engine power values per unit area, the number of tractors per 1000 ha, the agricultural area per tractor, and the amount of equipment per tractor. Mccormack et al. (2012) adopted a more subjective manner. The authors categorized the operations on farms into three levels of mechanization—low, moderate, and high. In their categorizations, a highly mechanized operation means most of the work was done with machines, while a low mechanization level means there was little use of farm machinery. Zangeneh et al. (2010) identified 19 farming activities as explanatory parameters and developed an artificial neural network model based on these parameters to assess the mechanization levels of the potato farms in Iran. Zangeneh et al. (2015) also developed an artificial neural network model to assess the level of mechanization in Italy’s potato production. To assess mechanization, the model utilized four indicators—machinery energy ratio, mechanization index, productivity level of consumed power, and mechanization level. Mehdi et al. (2013) proposed a method that could assess the mechanization levels of the coal-mining process, based on the adoption of Analytic Hierarchy Process approach. The method was established based on seven critical factors—seam inclination, seam thickness, geological disturbances, roof conditions, floor conditions, water at working face, and extension of seam. These factors could affect the assessment of mechanization.

Based on the foregoing review, one sees that the literature mainly reports the assessment of mechanization in the industries of agriculture and mining. Very few investigated the assessment of mechanization in the petrochemical industry. But nonetheless, these studies are informative and helpful to the current research, especially the Zangeneh et al. (2010) study. That study, which used a group of activities to assess mechanization levels in potato farming, inspired the research team to believe that the various maintenance tasks of petrochemical facilities could and should be identified first and then used to facilitate the assessment of mechanization in petrochemical facilities.

2.3. Prevailing practices adopted for subject assessment

In the field of engineering management, many researchers have assessed a variety of subjects using different approaches or methods. Li et al. (2016) proposed a risk-assessment approach to manage construction projects. Their approach interprets the subjective assessments of domain experts with a statistical method inspired by cognitive psychology theory. The approach can estimate the probability distributions of the attributes of the perceived risks and analyze risks' criticalities. Woldesenbet et al. (2016) presented a framework that assesses the level of effective use of data in managing highway-infrastructure projects. They established the framework using social network theory and the assessment mainly relies on perception data collected from the decision-makers in highway agencies. Collins et al. (2017) identified 41 elements relevant to planning small industrial projects and, using these elements, the researchers developed an assessment tool. Using the perception data provided by domain experts, the tool assesses how well the project-scope definition is developed during front-end planning for small industrial projects. Krajangsri and Pongpeng (2017) developed a framework that assesses the sustainability of infrastructure projects. The framework consists of eight constructs (e.g., transport, community, energy and water, location, etc.) and the assessment results are derived from the perception data collected from industry practitioners. Liu et al. (2019) developed a probabilistic-based cascading failure approach to assess the effects of human error-induced hazards at construction sites. As inputs, the assessment process requires actual safety inspection data acquired from construction sites. Cheung and Shen (2017) used contract data collected from active players in Hong Kong's construction industry to assess the concentration of the mega-project construction market using the four-firm concentration ratio and the Herfindahl Index.

Due to limited space, the research team is unable to list here all the relevant assessment studies. However, a pattern did emerge that the types of the data used by these assessment studies generally fell into two categories—perception data and actual data. Thus, it can conclude that the type of the data available determines the strategy to be used for assessment.

2.4. Petrochemical industry of Singapore

This study was conducted within the context of Singapore, which is home to a large and thriving petrochemical industry. Because of its favorable geographic location, Singapore has attracted many world-class petrochemical companies to establish plants in the country (Yun and Jin, 2009). Like many other countries, though, that promote the petrochemical industry, Singapore faces a challenge in maintaining the industry's productivity, especially when it comes to maintenance (Pokharel and Jiao, 2008). To address the challenge, Singapore formed, in February 2015, the governmental organization Productivity Council. Productivity Council consists of the members from government agencies, energy & chemical companies, and main contractors active in Singapore's petrochemical industry. In addition, the government established, under the aegis of the Productivity Council, the working group Mechanization Working Group.

This group seeks out areas of possible improvement in productivity by assessing and increasing the mechanization level in the local petrochemical industry. The Mechanization Working Group consists of five major owner companies and five major contractor companies; together, these companies encompass most of the active players of the Singapore process industry. Furthermore, the working group involves an industry association that represents the interest of all small contractors in the process industry of Singapore. Therefore, the working group fairly represents Singapore's process industry. Throughout the research process of this study, the Mechanization Working Group provided extensive help with such activities as developing the assessment method, collecting data, carrying out pilot studies, and validating the assessment method.

3. Methodology

The objective of this research is to develop a method that can assess the level of mechanization of maintenance tasks in petrochemical facilities and provide corresponding recommendations for improvement. This method was called Petrochemical Maintenance Mechanization Assessment (PEMMA). The mechanization level of each maintenance task is ultimately determined by the mechanization level of the tools and equipment used for the task. Therefore, as the first research step, this study proposed a rating scale that can be used to assess the mechanization level of the tools and equipment used for maintenance tasks. Then, this study identified the major work types highly correlated with maintenance in petrochemical facilities, together with the specific maintenance activities and sub-tasks for each work type. This study also identified the tools and equipment that are commonly used for each maintenance sub-task. After that, this study developed a scoring system that can calculate the mechanization level of a given project. Then, based on the developed method of PEMMA, this study developed Mechanization Index Assessment Tool (MIAT), a user-friendly tool that can help industry practitioners assess their maintenance tasks and help them locate improvement opportunities. Lastly, the PEMMA method and MIAT tool were valeted with practitioners from the petrochemical industry. Fig. 1 illustrates the research steps of this study.

3.1. Defining mechanization rating scale for maintenance tools and equipment

Modifying the scales proposed by Lindström and Winroth (2010), a seven-level rating scale was developed, as presented in Table 1, to assess the mechanization level of the tools and equipment used for maintenance tasks. There are two reasons for adopting the scales of Lindström and Winroth (2010) rather than developing a new scale. First, the scales of Lindström and Winroth (2010) were designed to assess the automation levels of the various tasks in the manufacturing industry, which is highly similar to the purpose and principle of the method to be developed by the current study. Second, with their publication, Lindström and Winroth (2010) demonstrated that academia recognizes the scales, implying that results generated are accurate and reliable.

It can be seen from Table 1 that the proposed measurement scale ranges from one to seven, covering all mechanization levels from completely manual to fully automated. Also presented in Table 1 are the percentages of the scales of measurement. The percentages are provided because, for audiences from the industry, they are more direct and easier to understand, according to Zhao et al. (2018). Apart from that, the example tools/equipment are also presented in the 'definition' column of the table, explaining each scale of the measurement.

3.2. Identifying the major work types, activities, and sub-tasks

In today's petrochemical plants, crews must carry out various types of maintenance tasks. Some of these tasks share certain similarities in practice standards and settings. Thus, to clarify and simplify the assessment process, this study categorized the different types of maintenance tasks, as presented in Fig. 2, and established a bottom-up, hierarchical framework to depict the maintenance of petrochemical facilities. From bottom to top, the framework consists of five tiers, including the mechanization level of the tools and equipment used for sub-tasks, the tools and equipment used for sub-tasks, activities, and work types. According to the proposed hierarchical framework, the mechanization level of the tools and equipment determines the mechanization level of the

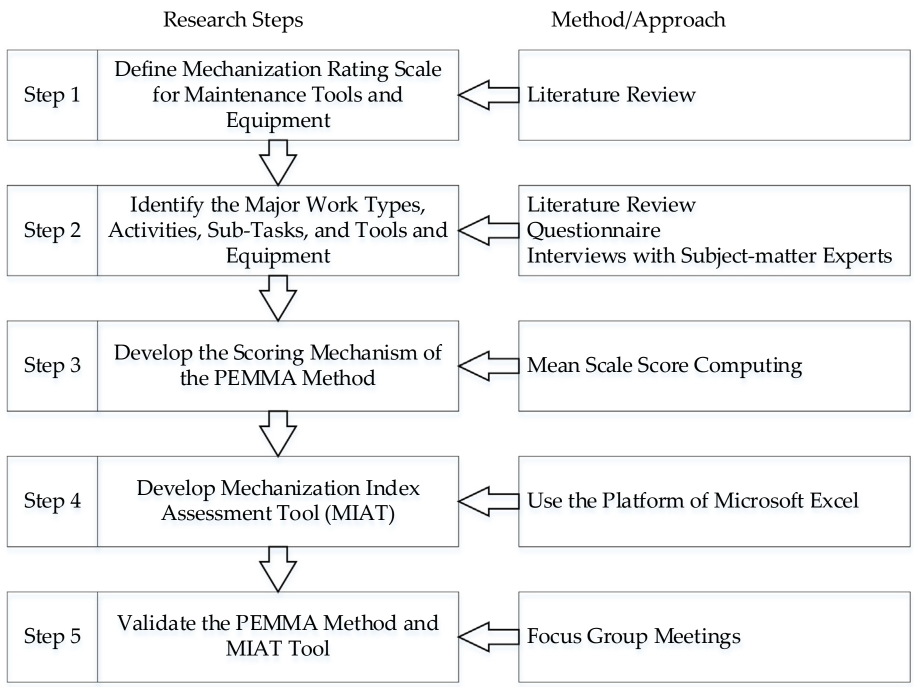


Fig. 1. Research flowchart of the study.

Table 1
Mechanization rating scale for maintenance tools and equipment.

Scale of Measurement		Scale Description	Definition
In number	In percentage		
1	14%	Completely manual	Totally manual work. No tools are used and only rely on the muscle power of the users.
2	29%	Static hand tool	Manual work with the support of static tool such as paint brush or paint roller.
3	43%	Flexible hand tool	Manual work with the support of flexible tool such as adjustable span paint roller.
4	57%	Automated hand tool	Manual work with the support of automated tool such as hand-held spray-painting gun.
5	71%	Static machine/ workstation	Automatic work by machine that is designed for a specific task, e.g., robotic painting machine
6	86%	Flexible machine/ workstation	Automatic work by a machine that is capable of performing more than one task, e.g., dual function blasting and painting robot.
7	100%	Fully automated	Totally automated work, the machine solves all deviations or problems that occur independent of human operator, e.g., painting robot with flexible arm.

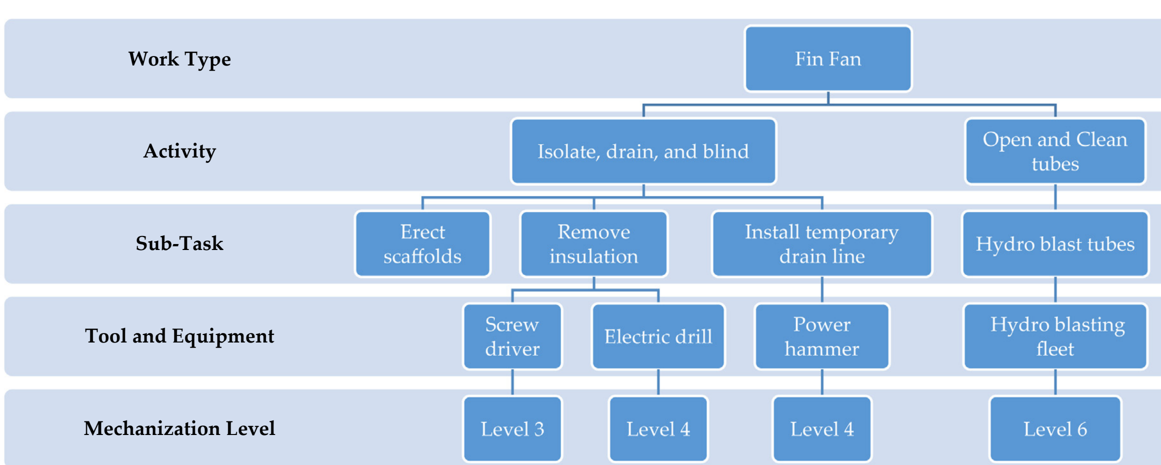


Fig. 2. Hierarchical framework for mechanization assessment.

sub-task, which further determines the mechanization level of the activity, and then the work type. Lastly, the mechanization levels of all work types determine the overall mechanization level of the facilities.

This study defines work types as the main scopes of maintenance work performed at petrochemical facilities. To identify the major work types, a questionnaire was developed and then deployed to the members of the Mechanization Working Group. The questionnaire asked members to list the major physical systems of a petrochemical facility that demand significant maintenance work. With the results obtained from the questionnaire the research team conducted a comprehensive literature review to validate the members' input. Results show that the major work scopes commonly performed in petrochemical facilities fall into ten major work types—1) tank, 2) exchanger, 3) tower, 4) fin fan, 5) furnace, 6) reactor, 7) underground piping repair, 8) pipe fabrication, 9) electrical instrumentation and repair, and 10) corrosion under insulation inspection.

This study defines an activity as a high-level grouping of the maintenance work performed within some work type. After defining the major work types, the research team identified major activities under each work type, drawing on interviews with two experienced subject-matter experts. The experts, for example, summarized the activities contained within the work type of fin fan as follows: 1) isolate, drain, and blind; 2) open and clean tubes; and 3) inspect, repair, and test. Although there are other maintenance activities performed on fin-fans, the subject matter experts asserted that these three activities encompassed most of the work for fin-fans that are critical to schedule and budget. Lastly, with the aid of the subject-matter experts researchers identified 152 activities that all the ten work types comprise. The whole activity list was also reviewed by the Mechanization Working Group in order to make sure that all the activities are applicable to real practice.

Again, with support from the two subject-matter experts and members of the Mechanization Working Group, the research team identified the major activities and their corresponding sub-tasks. This study defines sub-tasks as low-level maintenance tasks that can be performed with a singular tool or piece of equipment. Under the fin-fan work type, for example, there are sub-tasks for the first activity of "isolate, drain, and blind." They are 1) erect scaffold, 2) remove insulation, and 3) install temporary drain line. Table 2 shows how one work type is broken down—the fin-fan work type, which has three activities and ten sub-tasks. A comprehensive list of all work types, activities, and the relevant sub-tasks identified can be seen in the Appendix.

Next, this study compiles a catalogue of tools and equipment that can be used to perform each maintenance sub-task. This step is important for two reasons. First, the scoring mechanism of the assessment method is dependent on the mechanization levels of the tools and equipment available for maintenance tasks. Second, the catalogue can also function as a resource for industry practitioners, to help them search the tools and equipment that can increase the mechanization levels of their maintenance tasks. To compile a comprehensive list of tools and equipment for all 152 sub-tasks presented in Table 4 in Appendix, the research team used three methods. First, an extensive online search was conducted to identify the prevailing tools and equipment available in the existing market. The online search was done over a span of four months, from December 2016 to March 2017. Simultaneously, the research team distributed a questionnaire to members of the Mechanization Working Group. This was to collect information about the current tools and equipment the local practitioners are using, as well as the coming tools and equipment to be available soon. Additionally, a subject matter expert was contracted with the research team to help validate the tools and equipment gathered from the questionnaire and from online searches. To gather information on new tools and equipment unavailable to the public through online sources, the subject expert contacted construction and maintenance vendors and manufacturers in his own network. Finally, 130 unique tools and pieces of equipment were gathered.

Table 2
Activities and sub-tasks of the work type fin fan.

Work Type/Activity/Sub-task
IV. Fin Fan
4.1 Isolate, Drain, and Blind
4.1.A Erect Scaffolds
4.1.B Remove Insulation
4.1.C Install Temporary Drain Line
4.2 Open and Clean Tubes
4.2.A Remove Header Plugs on Both Ends
4.2.B Hydro Blast Tubes
4.3 Inspect, Repair, and Test
4.3.A Inspect and Identify Repairs
4.3.B Prep. Surface for Repairs as Required by Inspection
4.3.C Repair as Required by Inspection
4.3.D Re-Install Header Plugs on Both Ends
4.3.E Hydrotest

3.3. Developing the scoring mechanism of PEMMA

To facilitate the mechanization assessment, the research team developed a scoring system. The scoring mechanism follows an approach developed by Caldas et al. (2015). This method assesses the implementation levels of best productivity practices in industrial projects. The calculation procedures of the scoring mechanism are as follows.

(1) Calculate the mechanization index at the sub-task level using Equation (1) as shown below:

$$M_{ij} = A_{ij}/7 \tag{1}$$

Where M_{ij} is the mechanization score of the jth sub-task under the ith work type, and A_{ij} is the user's assessment of the jth sub-task under the ith work type.

(2) Calculate the mechanization index at the work type level using Equation (2):

$$M_i = \frac{\sum_{j=1}^{m} M_{ij}}{m} \tag{2}$$

Where M_i is the mechanization index of the ith work type, M_{ij} is the mechanization index of the jth sub-task under the ith work type, and m is the number of the sub-tasks under the ith work type.

(3) Calculate the mechanization index at the project level using Equation (3) presented below:

$$M = \frac{\sum_{i=1}^{n} M_i}{n} \tag{3}$$

Where M is the mechanization index of the assessed project, M_i is the mechanization index of the ith work type, and n is the number of work types.

As presented above, it can be seen that, to assess mechanization in petrochemical facilities, the scoring mechanism adopts a bottom-up strategy, and that it is able to obtain the degree of mechanization at all levels—sub-task, work type, and project. Hence, the research team could obtain and compare the mechanization indices for different work types and different projects. This is especially helpful to companies trying to locate work types or projects having low mechanization levels.

3.4. Mechanization Index Assessment Tool development

The final step was to develop, based on the developed method of PEMMA, a user-friendly tool that would be able to help industry practitioners assess, analyze, and improve the mechanization levels of the maintenance tasks in petrochemical facilities. This tool is referred to as Mechanization Index Assessment Tool (MIAT). The MIAT tool was developed using Microsoft Excel. Excel was used given two considerations. First, the software is widely available to the public, enabling mass users in the industry to access it. Second, the developed tool can update automatically whenever Microsoft updates Excel, thus saving the tool developer tedious maintenance and update work.

As presented in Fig. 3 through 6, the MIAT tool consists of five sections—Introduction, User Guide, Input Rating, Output Reporting, and Output Comments. Fig. 3 shows the Introduction Sheet contains an introduction to the tool and a project-evaluator information table. The User-Guide Sheet provides the user with instructions on how to use the tool. It explains key terms, such as work types, activities, sub-tasks, and mechanization levels. Fig. 4 shows the Input Rating Sheet, where the user can score the mechanization level of each sub-task. The sheet is organized at the highest level by work type, followed activity and sub-task. It also has a dialogue box displaying the specific tools and equipment that can be used for a given sub-task, as well as the mechanization levels of the tools and equipment. Moreover, a Comment column of was also placed in the Input Rating sheet, to allow the user to add those existing tools and equipment not included by the tool. The Output Reporting Sheet, seen in Fig. 5, is a summary of all the inputs entered by the user. It also presents the assessment results at the level of work types which are calculated by the scoring system. The last sheet is the Output Comments Sheet. It presents the new equipment and tools that are added by the user, as shown in Fig. 5.

3.5. Method validation

The validation of the PEMMA method was conducted in August 2017 by organizing focus-group meetings with two owner companies of the Mechanization Working Group. During meetings, representatives of the two companies were asked to review the PEMMA method. The company representatives were asked to check the appropriateness and accuracy of the statements involved in PEMMA. Additionally, company representatives were asked to verify the tools and equipment that had been assigned to the sub-tasks in PEMMA. They were also asked to supplement the tools and equipment omitted by PEMMA. Results of the validation show that representatives from both companies acknowledged the practicality of PEMMA. They also provided some comments and suggestions that could help improve the method. They suggested, for example, that the research team rephrase 12 sub-tasks under the work types of tank, exchanger, tower, furnace, and underground piping repair. They found some tools and equipment were improperly assigned to 20 sub-tasks under the work types of tank, exchanger, tower, fin-fan, furnace, reactor, underground piping repair, and corrosion under insulation inspection. They recommended new tools and equipment to three sub-tasks under the work types of tank and electrical instrumentation and repair. Based on these comments and suggestions, the research team thus revised the PEMMA method and the MIAT tool accordingly.

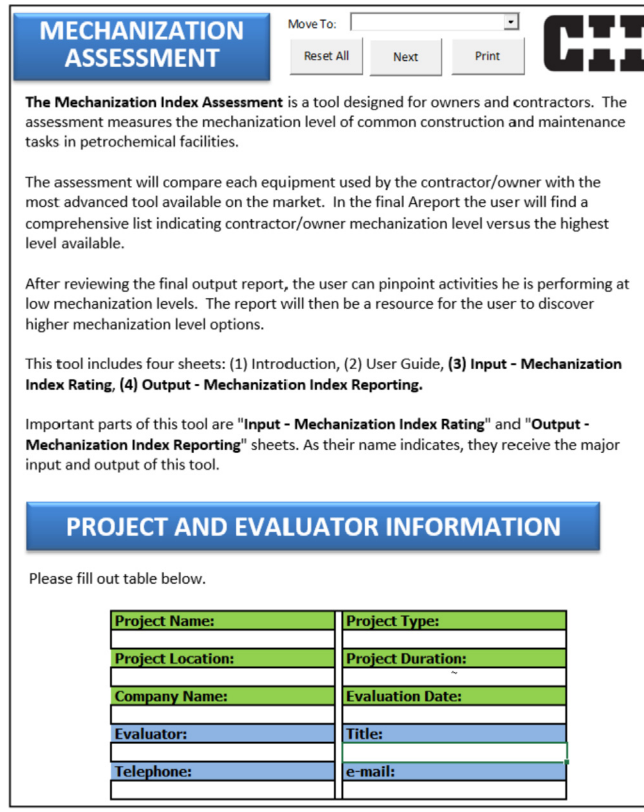


Fig. 3. Introduction sheet of MIAT.

4. PEMMA application in Singapore: results and discussions

The PEMMA method was applied in the context of Singapore in September 2017. All company members in Mechanization Working Group, including five owner companies and five contractor companies, were invited to review the PEMMA method and to use the MIAT tool to assess the mechanization levels of the maintenance tasks in their plants. Ultimately, five owner companies and four contractor companies (90 percent of company members in Mechanization Working Group) submitted their responses. The companies' responses indicated wide recognition from industry practitioners towards the PEMMA method and the MIAT tool. Only the statements of a few sub-tasks needed minor revision to be more accurate. The nine companies acknowledged and repeatedly stressed the application value of the method and the tool in practice.

As noted above, the Mechanization Working Group is representative of the Singapore process industry. Thus, the assessment results obtained from the working group in the method application, presented in Table 3, can be fairly regarded as the mechanization assessment results of the process industry of Singapore. Table 3 shows that the overall mechanization level of the maintenance tasks in petrochemical facilities of Singapore is 51.16%. Comparing this result to the measurement scale defined in Table 1, the result is between 43% (i.e., flexible hand tool at Level 3) and 57% (i.e., automated hand tool at Level 4). Such a result reveals that the mechanization level of the maintenance tasks in Singapore is relatively low and the primary tools used for maintenance are hand tools.

As for the mechanization levels of different work types, it can be seen from Table 3 that, the results of "exchanger," "pipe fabrication," "electrical instrumentation and repair," and "underground

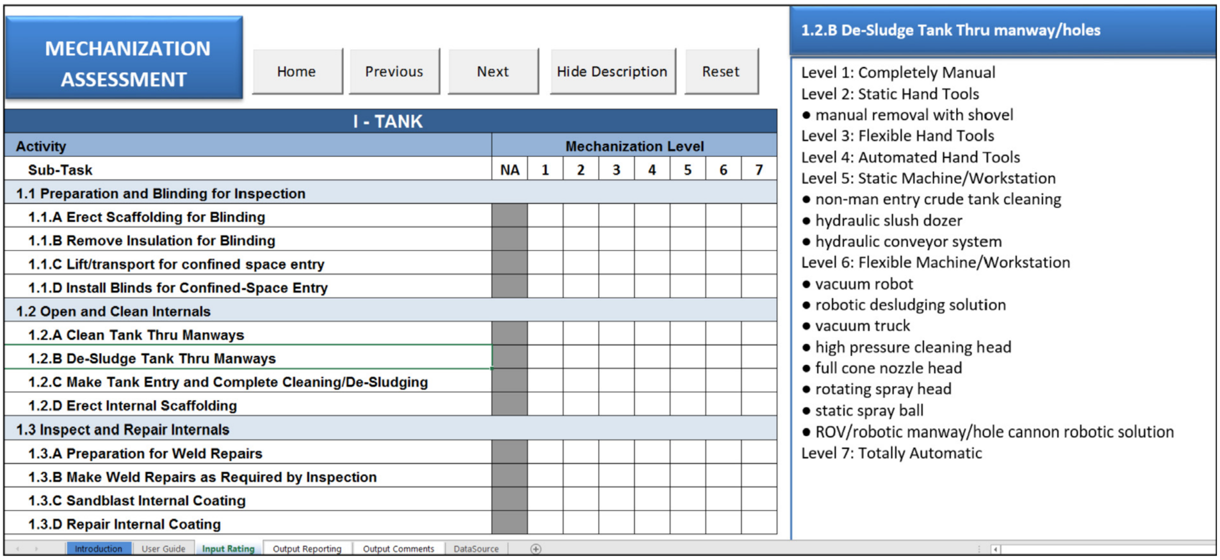
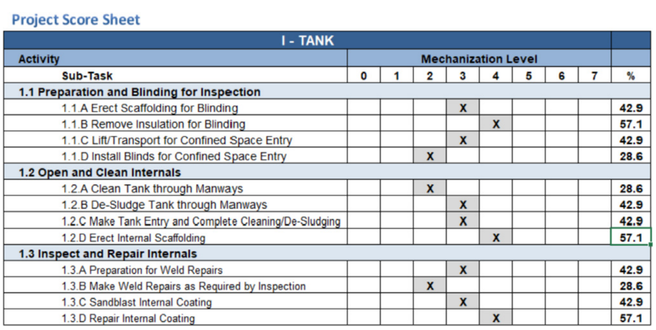


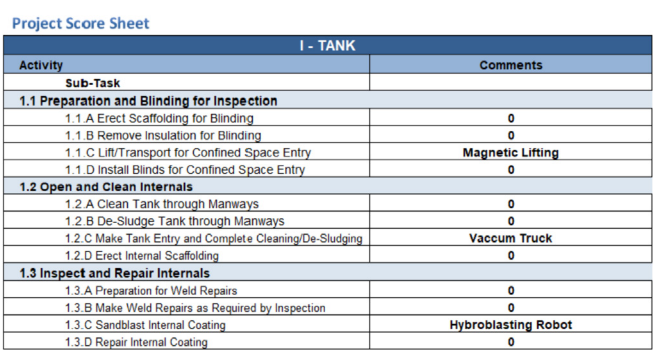
Fig. 4. Input rating sheet of MIAT.



Project Score Sheet

I - TANK									
Activity	Mechanization Level								
Sub-Task	0	1	2	3	4	5	6	7	%
1.1 Preparation and Blinding for Inspection									
1.1.A Erect Scaffolding for Blinding				X					42.9
1.1.B Remove Insulation for Blinding					X				57.1
1.1.C Lift/Transport for Confined Space Entry				X					42.9
1.1.D Install Blinds for Confined Space Entry			X						28.6
1.2 Open and Clean Internals									
1.2.A Clean Tank through Manways			X						28.6
1.2.B De-Sludge Tank through Manways				X					42.9
1.2.C Make Tank Entry and Complete Cleaning/De-Sludging				X					42.9
1.2.D Erect Internal Scaffolding					X				57.1
1.3 Inspect and Repair Internals									
1.3.A Preparation for Weld Repairs				X					42.9
1.3.B Make Weld Repairs as Required by Inspection			X						28.6
1.3.C Sandblast Internal Coating				X					42.9
1.3.D Repair Internal Coating					X				57.1

Fig. 5. Output reporting sheet of MIAT.



Project Score Sheet

I - TANK	
Activity	Comments
Sub-Task	
1.1 Preparation and Blinding for Inspection	
1.1.A Erect Scaffolding for Blinding	0
1.1.B Remove Insulation for Blinding	0
1.1.C Lift/Transport for Confined Space Entry	Magnetic Lifting
1.1.D Install Blinds for Confined Space Entry	0
1.2 Open and Clean Internals	
1.2.A Clean Tank through Manways	0
1.2.B De-Sludge Tank through Manways	0
1.2.C Make Tank Entry and Complete Cleaning/De-Sludging	Vaccum Truck
1.2.D Erect Internal Scaffolding	0
1.3 Inspect and Repair Internals	
1.3.A Preparation for Weld Repairs	0
1.3.B Make Weld Repairs as Required by Inspection	0
1.3.C Sandblast Internal Coating	Hybroblasting Robot
1.3.D Repair Internal Coating	0

Fig. 6. Output comments sheet of MIAT.

piping repair" are greater than the industry average. The most mechanized work type was that of "exchanger," as it received the highest assessment of 59.37%. Lower than the industry average, in contrast, are the assessments of "tank," "reactor," "fin-fan," "furnace," "tower," and "corrosion under insulation inspection." Particularly for "corrosion under insulation inspection," it was found to be the least mechanized work type as it received the lowest assessment of 37.50%. These results suggest that the practices within those work types rely more on manpower or tools at low level of mechanization. It also reminds the industry practitioners that more attention should be given to those work types to change their practice style, thereby making the whole petrochemical industry more productive and cleaner.

Data were collected from both owner companies and contractor companies in the Mechanization Working Group. Hence, it seems proper to compare the results of the two groups to check for any statistical differences. To facilitate the comparison, researchers adopted the method of Wilcoxon signed-rank test using the software IBM SPSS Statistics. Researchers commonly use the Wilcoxon signed-rank test to compare two related samples, matched samples, or repeated measurements on a single sample, as they look for any significant differences between the variables (Darko and Chan, 2018). For the owner-contractor comparison then, the method is appropriate. According to the test results shown in Table 3, owners and contractors provided similar assessment results for most of the work types, with "corrosion under insulation inspection" being the exception. Such a result suggests that owner companies and contractor companies share similar perceptions regarding the mechanization levels of the maintenance tasks in the petrochemical facilities of Singapore. As for the difference in the work type of "corrosion under insulation inspection," it can be seen from Table 3 that the mechanization level with the contractors was significantly lower than with owners. This is because the contractors in the petrochemical industry of Singapore mainly rely on manpower to do insulation inspection.

As for those work types and tasks that received low mechanization assessments, improvement solutions can be found in the MIAT tool. The least mechanized work type, for example, was assessed as "corrosion under insulation inspection." To improve the mechanization level in this work type, users could first identify the sub-task receiving low assessment. They can then check whether any tools and equipment available at higher mechanization levels are available for the sub-task within the MIAT tool. If tools and equipment are available, they can be considered solutions for improvement.

5. Conclusions and recommendations

This study concentrates on the mechanization of maintenance tasks performed in petrochemical facilities, which is critical to building up a more productive and cleaner petrochemical sector. This study developed a method called PEMMA, a standardized

Table 3
Mechanization assessment results in Singapore.

Work type	Overall			Owner			Contractor			Comparison	
	Mean[a]	Rank	Standard Deviation	Mean[a]	Rank	Standard Deviation	Mean[a]	Rank	Standard Deviation	Difference	Wilcoxon Signed-rank test (p-value)
Tank	50.90%	5	7.10%	53.71%	5	8.67%	48.10%	5	3.16%	5.62%	0.345
Exchanger	59.37%	1	3.51%	61.28%	1	0.92%	57.46%	1	4.06%	3.82%	0.197
Tower	46.95%	9	5.58%	49.19%	8	5.47%	44.71%	9	4.72%	4.48%	0.223
Fin fan	48.40%	7	4.62%	52.66%	7	2.31%	44.98%	8	2.83%	7.67%	0.500
Furnace	47.21%	8	4.50%	48.47%	9	3.12%	45.95%	6	5.25%	2.52%	0.416
Reactor	49.34%	6	7.26%	53.42%	6	4.94%	45.27%	7	6.91%	8.16%	0.223
Underground piping repair	56.88%	4	7.66%m	60.71%	3	2.33%	53.82%	3	8.95%	6.90%	0.686
Pipe fabrication	57.92%	2	6.63%	59.22%	4	2.41%	56.62%	2	8.87%	2.60%	0.715
Electrical instrumentation and repair	57.09%	3	9.16%	60.86%	2	5.76%	50.82%	4	10.26%	10.04%	0.080
Corrosion under insulation inspection	37.50%	10	8.65%	42.38%	10	6.10%	29.37%	10	5.61%	13.02%	0.043[b]
Industry level	51.16%			54.19%			47.71%			6.48%	

Note:
[a] Scales of measurement: completely manual (14%), static hand tool (29%), flexible hand tool (43%), automated hand tool (57%), static machine/workstation (71%), flexible machine/workstation (86%), and fully automated (100%).
[b] The Wilcoxon signed-rank test was significant at the significance level of 0.05, suggesting the mechanization levels of the work type between owner and contractor were statistically different.

method that can help assess the level of mechanization in the maintenance of petrochemical facilities. To develop PEMMA, the research team followed four steps. First, to assess the mechanization of maintenance tasks, researchers defined a seven-level rating scale. Then, the research team identified the major work types, activities, and sub-tasks involved in petrochemical facility maintenance, together with the existing tools and equipment used for specific maintenance sub-tasks. The research team then developed a bottom-up scoring mechanism to calculate the mechanization level of the maintenance tasks in a given project. Finally, based on PEMMA, the research team developed an Excel-based tool, MIAT, to facilitate the assessment of the mechanization levels of the maintenance tasks. The MIAT tool was used to assess the mechanization levels of maintenance at Singapore's petrochemical facilities. The overall mechanization level in Singapore was found to be a relatively low 51.16%. The results also revealed that in Singapore's realm of petrochemical maintenance, the most mechanized work type is "exchanger," while the least mechanized is "corrosion under insulation inspection."

Although the objective of this study has been achieved, there are limitations. First, due to the experience and knowledge limitations of the research team, including those of the subject matter experts, the research team may have omitted some activities, sub-tasks, and the relevant tools and equipment. Second, the validation of the method was conducted via interviews. The interviewees' views might be subjective which may reduce the trustworthiness and reliability of the results of validation.

Despite these limitations, this study contributes both to the current body of knowledge and to the practice. The assessment method developed in this study is arguable the first method to evaluate the level of mechanization in maintenance of petrochemical facilities. Thus, it adds to the existing literature of mechanization and maintenance. This study is beneficial to the industry as well. The PEMMA method and the MIAT tool can help industry practitioners assess the mechanization level of their maintenance practices. Moreover, the catalogue information of the tools and equipment included in the proposed method can also help industry practitioners locate mechanization-improvement opportunities. Although the PEMMA method and the MIAT tool were developed in the context of Singapore, they, however, have global contribution. This is because the method development process involved inputs from five world leading petrochemical companies, who have considerable plants across the world where standard practice codes and norms are shared. Therefore, PEMMA and MIAT is applicable to the global petrochemical industry having application potential worldwide.

For future research, it would be interesting to conduct an international assessment of petrochemical maintenance in the global petrochemical industry to make inter-country comparisons. It would also be interesting to investigate the correlations of mechanization improvement with maintenance performance, to check the efficacy of implementing mechanization. It is also important and necessary to investigate the management issues (e.g., scheduling, cost-benefit analysis) related to mechanization in the future.

Declaration of competing interest

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

CRediT authorship contribution statement

Ming Shan: Methodology, Data curation, Formal analysis, Writing - original draft. **Bon-Gang Hwang:** Conceptualization, Methodology, Data curation, Writing - review & editing. **Carlos H. Caldas:** Conceptualization, Methodology, Writing - review & editing. **Zhe Yin:** Writing - review & editing, Formal analysis. **Daniel P. Oliveira:** Formal analysis.

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Appendix. Work types, activities, and sub-tasks used by PEMMA

Work Types	Activities	Sub-tasks
TANK	1-Preparation and Blinding for Inspection	Erect Scaffolding for Blinding
		Remove Insulation for Blinding
		Lift/transport for confined space entry
		Install Blinds for Confined-Space Entry
	2-Open and Clean Internals	Clean Tank Thru manway/holes
		De-Sludge Tank Thru manway/holes
		Make Tank Entry and Complete Cleaning/De-Sludging
		Erect Internal Scaffolding
	3-Inspect and Repair Internals	Preparation for Weld Repairs
		Make Weld Repairs as Required by Inspection
		Sandblast Internal Coating
		Repair Internal Coating
EXCHANGER	1-Isolate, Blind, and Remove Piping	Erect Scaffolding for Blinding
		Remove Insulation
		Prepare/Remove Blinds
		Transport Blinds
		Lift Isolation Blinds
		Install Isolation Blinds
		Remove Pipe Spools
		Lift and Transport Pipe Spools
		Install Temporary Blind Flanges on Piping
	2-Remove Heads and Re-Surface Flange Faces	Remove/Disconnect Dollar Plate and Channel Head as Unit
		Lift Dollar Plate and Channel Head as Unit
		Remove/Disconnect Bell Head
		Lift Bell Head
		Remove/Disconnect Floating Head
		Re-Surface Flange Faces on Exchanger
		Remove Flange Faces on Exchanger
	3-Remove, Hydroblast, Inspect, and Re-Install Bundle	Initial Inspection of Exchanger
		Pull Exchanger Bundle
		Transport Exchanger Bundle to Hydroblast Slab
		Hydroblast Shell/Components
		Hydroblast Bundle at Hydroblast Slab
		Post Cleaning Inspection
		Transport Bundle Back to Unit
		Install Bundle
	4-Re-Install Heads and Hydrotest	Lift Floating Head
		Install Floating Head
		Lift Bell Head
		Install Bell Head
		Remove/Disconnect Temporary Piping/Blind Flanges
		Lift Temporary Piping/Blind Flanges
		Lift Pipe Spools - Shell Side
		Install Pipe Spools - Shell Side
		Perform Shell Side Test
	5-Remove Blinds and Re-Install Piping	Lift Pipe Spools - Tube Side
		Install Pipe Spools - Tube Side
		Preform Tube Side Hydro Test
		Disconnect All Blind
		Lift and Remove All Blinds
TOWER	1-Isolate, Blind, and Install Temporary Piping	Erect Scaffolding for Blinding
		Remove Insulation as Required
	2-Open and Clean Internals	Clean/De-Sludge Tower thru manway/holes
		Cover Bottom Outlet Nozzle
		Open Internal manway/holes
		Remove Demister Pad
		Remove Packing Tray Hold-Downs
		Remove packing
		Remove Trays and Packing Support Grids
		Remove all Distributors
		Erect Internal Scaffolding-Bottom of Tower
		Clean for Inspections
	3-Inspect and Repair Internals	Repair as Required by Inspection
		Clean and Install Demister Pad
		Clean Packing
		Install Trays and Packing Support Grids
		Install Packing Tray Hold-Downs
		Install Trays and All Distributors
	4-Obtain Vessel Closure Sign-Off and Close Tank	Disconnect Air Movers and Close manway/holes
		Lift Air Movers and Close manway/holes
	5-De-Blind and Area Move-Out	Disconnect Blinds and Make-up Flanges
		Lift and Transport Blinds and Make-up Flanges
		Install Insulation
FIN FAN	1-Isolate, Drain, and Blind	Erect Scaffolds

(*continued on next page*)

(*continued*)

Work Types	Activities	Sub-tasks
		Remove Insulation
		Install Temporary Drain Line
	2-Open and Clean Tubes	Remove Header Plugs on Both Ends
		Hydroblast Tubes
	3-Inspect, Repair, and Test	Inspect and Identify Repairs
		Prepare Surface for Repairs as Required by Inspection
		Repair as Required by Inspection
		Re-Install Header Plugs on Both Ends
		Hydrotest
FURNACE	1-Preparation and Blinding for Inspection	Erect Scaffolding for Blinding
		Remove Insulation as Needed
		Install Temporary Drain Line
		Lift/Transport Isolation Blinds
		Install Isolation Blinds
	2-Open, Clear, and Inspect	Erect Internal Scaffolding
		Clean External Surface of Tubes
		Inspect and Identify Repairs
		Remove, Clean, and Re-Install Burners
		Inspect Burners
	3-Replace Bends and Tubes	Remove Bends and Tubes
		Clean-up and Prep Tubes for Welding
		Install and Weld-up Return Bends
	4-Hydrotest	Blind for Hydrotest
		Fill and Hydrotest
		Remove Test Blinds
	5-Close, De-Blind, and De-Mobilize	Remove Temporary Drain Line
		Close Heater and Stack Door
		Install Insulation
REACTOR	1-Preparatioon and Blinding for Inspection	Erect Scaffolding for Blinding
		Remove Insulation as Needed
		Install Isolation Blinds
	2-Open, Remove Catalyst, and Clean	Install Temporary Piping for Operations
		Remove Tray manway/hole and Prepare for Dump
		Remove and Dump Catalyst
		Clean Reactor/Top Tray for Inspection
	3-Inspect and Repair Internals	Inspect Reactor and Identify Repairs
		Prepare Surface for Weld Repairs
		Make Weld Repairs as Required by Inspection
	4-Load Catalyst and Close Reactor	Obtain Vessel Closure Sign-off and Re-install Tray manway/hole
	5-De-Blind and Area Move-Out	Remove Blinds
		Install Insulation
		Remove Temporary Piping
UNDERGROUND PIPING REPAIR	1-Identify Leak and Prep for Excavation	Demo Existing Concrete @ Leak
		Excavate as Needed to Expose Leak
	2-Make Excavation for Leak Repair	Excavate to Provide Access for Repair/Replacement
		Install Shoring Box
		Inspect and Identify Repair Scope
	3-Replace Piping	Cut Existing Piping and Demo Piping
		Lift Piping to be Demoed
		Obtain Pipe and Fittings, and Fab Pipe Spools
		Weld Pipe Spools
		Install Blinds and Weld Cap, and Hydrotest Piping Spool
		Remove Blinds and Weld Cap and Relocate to Site
		Install Piping Spool at Work Site - Lift/Transport
		Install Piping Spool at Work Site - Weld
		Install Pipe Wrap and Test for Cathodic Protection
	4-Backfilling and Compacting	Place Backfill Material at Work Site
		Remove Shoring Box
		Machine Backfill and Compact to Grade
		Place Concrete
	5-Waste Disposal	Dispose of Demo Piping
		Dispose of Contaminated Soil
		Dispose of Demo Concrete
PIPE FABRICATION	1-Pipe fabrication - Stainless Steel	Layout and Cut Piping to Lengths
		Clean and Prep Pipe and Fittings for Welding
		Make Fit-up and Set-up Inert Gas Purge
		Maintain Purge and Weld Pipe and Fittings
		Install Blinds and Hydrotest Piping Spools
		Remove Blinds and Relocate Spools to Staging Area
	2-Pipe fabrication - Carbon Steel	Layout and Cut Piping to Lengths
		Clean and Prep Pipe and Fittings for Welding
		Make Fit-up and Weld Pipe and Fittings
		Install Blinds and Hydrotest Piping Spools
		Remove Blinds and Relocate Spools to Paint Yard
ELECTRICAL & INSTRUMENTATION	1-Inspect and Repair Lighting	Replace Light Bulbs

(*continued*)

Work Types	Activities	Sub-tasks
		De-energize and Replace Light Fixture
	2-Inspect and Repair Motor	Pull Motor and Transport to Shop
		Overhaul Motor
	3-Replace Damaged Conduit at Motor	Remove damaged Conduit
		Fab Replacement Conduit
		Install New Conduit
	4-Re-Install Motor	Transport Motor to Field Location
	5-Cable Pulling	Transport Cable Drum to Field Location
		Cable Pulling to Equipment Location
CUI INSPECTION	1-Perform CUI Inspection	Identify Inspection Locations
		Erect Scaffolding
		Identify and Mark Locations on Insulation Jacketing
		Drill Inspection Hole thru Insulation to Expose Metal
		Inspect Piping/Vessel Wall Thickness for Corrosion
		Repair Insulation and Plug Inspection Hole

References

Arts, R., Knapp, G.M., Mann Jr., L., 1998. Some aspects of measuring maintenance performance in the process industry. J. Qual. Mainten. Eng. 4, 6–11.

Caldas, C.H., Kim, J.Y., Haas, C.T., Goodrum, P.M., Zhang, D., 2015. Method to assess the level of implementation of productivity practices on industrial projects. J. Construct. Eng. Manag. 141, 04014061.

Cambridge Dictionary, U., 2018. Definition of "maintenance" - English Dictionary [Online]. Available: https://dictionary.cambridge.org/us/dictionary/english/maintenance. Accessed September 27 2018.

Cheung, S.O., Shen, L., 2017. Concentration analysis to measure competition in megaprojects. J. Manag. Eng. 33, 04016023.

Collins, W., Parrish, K., Gibson, G.E., 2017. Development of a project scope definition and assessment tool for small industrial construction projects. J. Manag. Eng. 33, 04017015.

Darko, A., Chan, A.P.C., 2018. Strategies to promote green building technologies adoption in developing countries: the case of Ghana. Build. Environ. 130, 74–84.

Guiras, Z., Turki, S., Rezg, N., Dolgui, A., 2019. Optimal maintenance plan for two-level assembly system and risk study of machine failure. Int. J. Prod. Res. 57, 2446–2463.

Ha, J.M., Hwang, K.R., Kim, Y.M., Jae, J., Kim, K.H., Lee, H.W., Kim, J.Y., Park, Y.K., 2019. Recent progress in the thermal and catalytic conversion of lignin. Renew. Sustain. Energy Rev. 111, 422–441.

Hajej, Z., Turki, S., Rezg, N., 2015. Modelling and analysis for sequentially optimising production, maintenance and delivery activities taking into account product returns. Int. J. Prod. Res. 53, 4694–4719.

Iversen, F., Geehan, T., 2015. Drilling fluid processing: preparation, maintenance and continuous conditioning. IEEE Instrum. Meas. Mag. 18, 47–55.

Jalalzadeh, B., Borghei, A.M., Almassi, M., 2016. Modeling the effect OF mechanization level index ON crop yield approaching system dynamics methodology. J. Exp. Biol. Agric. Sci. 4, 169–179.

Krajangsri, T., Pongpeng, J., 2017. Effect of sustainable infrastructure assessments on construction project success using structural equation modeling. J. Manag. Eng. 33, 04016056.

Li, N., Fang, D., Sun, Y., 2016. Cognitive psychological approach for risk assessment in construction projects. J. Manag. Eng. 32, 04015037.

Lindström, V., Winroth, M., 2010. Aligning manufacturing strategy and levels of automation: a case study. J. Eng. Technol. Manag. 27, 148–159.

Liu, M., Chong, H.-Y., Liao, P.-C., Xu, L., 2019. Probabilistic-based cascading failure approach to assessing workplace hazards affecting human error. J. Manag. Eng. 35, 04019006.

Loera-Hernández, I., Espinosa-Garza, G., 2014. Labor Productivity in Projects of Construction and Industrial Maintenance. Key Engineering Materials. Trans Tech Publ, pp. 139–144.

Mannan, S., 2012. Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control, fourth ed.

Mccormack, L.A., Binkley, T.L., Specker, B.L., 2012. Effect of level of farm mechanization early in life on bone later in life. J. Musculoskelet. Neuronal Interact. 12, 7–15.

Mehdi, H.S., Reza, M., Mohammad, A., Khalokakaei, R., Akhyani, M., 2013. Development a new classification for assessing the coal mine mechanization. Arch. Min. Sci. 58, 217–226.

Moubray, J., 1997. Reliability-centered Maintenance. Industrial Press Inc.

Nižetić, S., Djilali, N., Papadopoulos, A., Rodrigues, J.J.P.C., 2019. Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management. J. Clean. Prod. 231, 565–591.

Pokharel, S., Jiao, J., 2008. Turn-around maintenance management in a processing industry: a case study. J. Qual. Mainten. Eng. 14, 109–122.

Praveen, G., Reddy, R.T., Suresh, K., 2019. Experimental studies on incremental hole flanging of steel sheets. Adv. Mater. Process. Technol. 5, 418–428.

Richardson, D., 2013. Plant Equipment & Maintenance Engineering Handbook. McGraw-Hill Education.

Ruqaishi, M., Bashir, H.A., 2015. Causes of delay in construction projects in the oil and gas industry in the Gulf Cooperation Council countries: a case study. J. Manag. Eng. 31, 05014017.

Sawyer, J.D., 2016. Technology, innovation key to oil and gas production cost reduction. Manuf. Eng. 156, 13–15.

Sharabiani, V.R., Ranjbar, I., 2008. Determination of the degree, level and capacity indices for agricultural mechanization in Sarab region. J. Agric. Sci. Technol. 10, 215–223.

Simpson, N.G., Bennett, M., Turner, S.F., 2018. Use of continuous infrared temperature image to optimize furnace operations. Ceram. Eng. Sci. Proc. 47–57.

Turker, U., Avcioglu, A.O., Elicin, K., 2011. Changing status of agricultural mechanization level during GAP process in the Southeastern Anatolia Region in Turkey. J. Food Agric. Environ. 9, 245–249.

Veldman, J., Klingenberg, W., Wortmann, H., 2011. Managing condition-based maintenance technology: a multiple case study in the process industry. J. Qual. Mainten. Eng. 17, 40–62.

Wen, C., Wang, H., Wang, L., Lou, Z., Sun, Z., Zhou, Z., 2019. The reduction of waste lubricant oil distillate through the enhancement of organics degradation by ozonation with elevated temperature and stable pH for the zero discharge. J. Clean. Prod. 240.

Willis, R., 1875. Principles of Mechanism: Designed for the Use of Students in the Universities and for Engineering Students Generally. J. Wiley.

Wills, B.A., Finch, J.A., 2015. Wills' Mineral Processing Technology: an Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery.

Woldesenbet, A., Jeong, H.D., Park, H., 2016. Framework for Integrating and assessing highway infrastructure data. J. Manag. Eng. 32, 04015028.

Yin, Z., Caldas, C., De Oliveira, D., Hwang, B.-G., Shan, M., 2019. Mechanization level assessment and technology identification for productivity improvement in petrochemical facility maintenance. J. Qual. Mainten. Eng.

Yun, H.A., Jin, L.K., 2009. Evolution of the petrochemical industry in Singapore. J. Asia Pac. Econ. 14, 116–122.

Zangeneh, M., Omid, M., Akram, A., 2010. Assessment of agricultural mechanization status of potato production by means of artificial Neural Network model. Aust. J. Crop. Sci. 4, 372–377.

Zangeneh, M., Omid, M., Akram, A., 2015. Integrated assessment and modeling of agricultural mechanization in potato production of Iran by artificial neural networks. Agric. Res. 4, 283–302.

Zhao, X., Wu, P., Wang, X., 2018. Risk paths in BIM adoption: empirical study of China. Eng. Construct. Architect. Manag. 25, 1170–1187.