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THE BENEFITS OF EMPLOYING MULTI SKILLED TECHNICIANSTO MAINTENANCE PROCESSES

Abdulsalam A. Al-Sudairi
Associate Professor, College of Architecture & Planning, University of Dammam, P. O. Box: 2397, Dammam 31451, Saudi Arabia, dr.alsudairi@yahoo.com

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Abstract

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Keywords

Preventive, corrective, maintenance, simulation, MST

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Abstract

Many researchers and practitioners applied lean theory to planning, designing and executing construction projects. However, few of their studies have been conducted in maintaining such projects. Maintaining and operating any constructed facility costs more than its initial cost. The aim of this study is to improve maintenance processes by simulating the lean concept of multi-skilled technician to an existing maintenance process. Statistical data and maintenance process map of Saudi Consolidated Electric Company (SCECO) are modeled in Extend+BPR® to be an experimental tool for evaluating the benefits of multi-skilled technicians. The simulation models of this study showed significant improvement in both preventive and corrective maintenance processes.

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INTRODUCTION

Improving maintenance programs has a huge margin of cost saving and value adding at different levels. In Saudi Arabia, a high percentage of the government's expenditure has been directed toward maintenance and operation projects (Al-Arjani, 2002). Therefore, any reduction in resources applied to building maintenance will have a visible effect on the national economy (Horner *et al.*, 1997). Reducing cost comes under different actions (e.g., process redesign/reengineering, better utilization of resources, reducing errors and reworks, … etc). This study aims at reducing cost of maintenance work orders by employing multi skilled technicians. The concept of multi skilled technician (MST) refers to a labor utilization strategy in which workers learn more multiple skills in one or more trades outside their primary trade (Carley *et al.*, 20003).

The cost and quality of maintenance activities are mainly dependent on labor. This is because the costs of maintenance labor constitute the largest block in the maintenance costs (Mjema, 2002). Therefore, enhancing labor performance will add value to the whole maintenance process. One way to enhance labor performance is to employ the concept of MST. This has proven its success in the manufacturing industry and is considered one of the major principles of lean production theory. The advantages of lean theory encouraged many researchers in the field of building industry to implement its principles in various levels including: planning, designing and executing of construction projects. However, few researchers focused on the impact of lean theory on maintenance processes.

The concept of MST can be applied to maintenance work orders (WO) where a technician can perform more than one work order of different services (e.g., mechanical, electrical, and so forth). For example, installing a water heater needs a plumber and electrician to complete the job in a traditional maintenance

[1] Associate Professor, College of Architecture & Planning, University of Dammam, P. O. Box: 2397, Dammam 31451, Saudi Arabia, dr.alsudairi@yahoo.com

system. With MST principle, this work order can be done by one technician instead of two. In this way work orders will wait less time in the maintenance system, thus increasing the throughput and enhancing the availability of a facility. Thus, the objective of this study is to assess the potentiality of having multi-skilled technicians who can perform several tasks compared traditional technicians who can perform limited tasks.

As a matter of fact a multi-skilled technician costs more than a single skilled technician. This study argues that the total cost of completing a job may decrease as the maintenance system with MST will be more responsive and faster, which will save time and effort. To test this hypothesis, a maintenance system for Saudi Consolidated Electric Company (SCECO), a leading company in Saudi Arabia, was selected as a case study. The main focus is head quarter maintenance division located at SCECO-East. This division is responsible for maintaining all administrative buildings, which consist of 30 buildings of various sizes and functions.

RELATED STUDIES

The philosophy behind lean production theory is to add more value and eliminate waste of a system (Alarcon 1997 and Salem *et al*. 2005). Waste is referred to as anything other than minimum amount of equipment, materials, parts, and working time that are absolutely essential to production (Taj, 2005). Eliminating waste and adding value is accomplished by integrating *people*, *machines* and *processes* together in order to reduce cost, material scrap, lead times, rework, flow times and optimizes the use of floor space (Mathaisel, 2005). It is believed that the triad of *people*, *machines* and *processes* of lean theory led to hybrid production of both *craft* production and *mass* production. In the former one, the main focus was on highly skilled craftsmen with simple tools who were capable of producing high quality products. In the latter one, more emphasis was given to sophisticated machines and tools with products that are highly interchangeable. Lean production is characterized by quality, as in craft production, and flexibility, as in mass production (Forza, 1996).

There are certain principles to be adopted in order to be lean and eliminate/reduce waste. The potential benefits of this adoption are rewarding. For instance, firms that eliminated sources of waste in the production flow gained significant reduction in cycle time, decrease in costs and increase in customer satisfaction (Koskela 1999, Mathaisel 2005 and Bhasin and Burcher 2006). One of the major principles that distinguish lean production management from traditional management is that it utilizes MST (Forza 1996). This principle was first implemented by the Japanese automobile industry where any worker in the production line can perform his own task and check tasks performed by other workers (Womack and Jones, 1996). By doing so, the finished final product was almost free from defects and no need for rework (Womack and Johns, 1990 and Farrar *et al*., 2004).

There are other advantages of employing the concept of MST which include: overcoming labor shortage (Lobo and Wilkinson, 2008), responding to unexpected events without consulting a supervisor (Carley *et al,*. 2003), improving quality (Carley *et al.*, 2003), enhancing process flexibility (Organ *et al*., 1998), reducing cost (Carley *et al.,* 2003 and Pintelon *et al*., 2006), and increasing productivity (Oral *et al.*, 2003 and Pintelon *et al*., 2006).

This study utilizes simulation modeling in evaluating the benefits of MST to maintenance processes. Several researchers modeled maintenance processes to evaluate certain issues. The simulation models of Ip *et al.* (2000) and Mjema (2002) focused mainly on capacity planning in order to determine the appropriate number of the maintenance personnel. Duffuaa *et al.* (2001) developed a generic conceptual simulation model that consisted of seven modules, such as materials and spares supply. The modules of Duffuaa's model are designed to fit common maintenance system requirements but not for specific issues like MST. Wang and Hwang (2004) integrated qualitative method in their mathematical model to include human factors (e.g., human errors) to find the optimum balance between the costs and benefits of maintenance. This study incorporates another qualitative factor, which is MST, in quantitative simulation models. The concept of MST and its impact on building maintenance was not thoroughly discussed in previous studies.

RESEARCH METHODOLOGY

Field surveys and interviews aimed at collecting data necessary for building two types of models: static and dynamic models. Static model, on one hand, is a two dimensional representation of the process by mapping it using flow chart techniques. A flow chart will show the logic, the activities and the decisions involved in performing maintenance work orders. This is an essential step in improving any process (Sodeholm *et al.*, 2007 and Parida, 2007). On the other hand, dynamic model is referred to computer simulation where one can experiment the potentiality and limitation of certain concepts. Figure (1) depicts the steps undertaken to build the aforementioned models and to achieve the study objective.

Out of the 60 employees working at the maintenance division, 23 were interviewed. The interviews were conducted in different phases to make sure that the collected information is accurate and to refine the maintenance process maps and the simulation model.

The development of the SCECO maintenance process map.

The maintenance process is divided into two main sub-processes: 1) Preventive Maintenance (PM), and 2) Corrective Maintenance (CM) as shown in figure 2. The two sub-processes are interrelated where under certain conditions some preventive maintenance work orders are converted into corrective maintenance work orders.

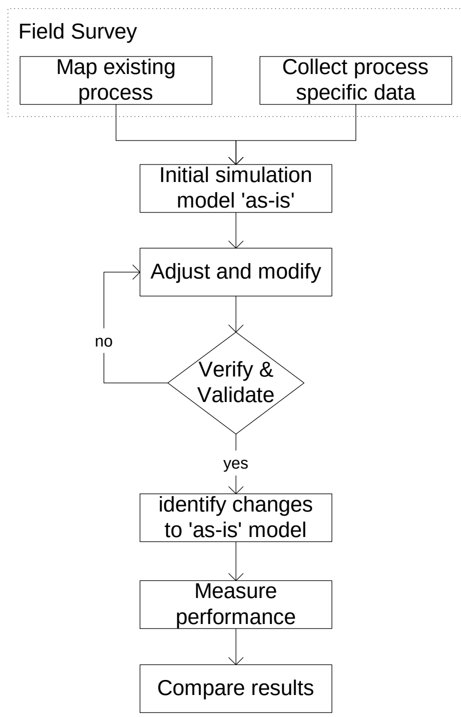


Figure 1: Research Methodology.

Such maps played a role in visualizing the work process flow and made discussions with interviewees easy and fruitful. The author facilitated further discussions by asking the following questions, which were taken from Back and Bell (1994) and Al-Sudairi (2007):

- Which activity must be finished before the next activity can begin?
- Can this activity occur concurrently with any other activities?
- Which resources are required to perform these activities?
- What are the deliverables of these processes?
- How are the deliverables transmitted internally and externally?
- How often must certain activities be repeated?
- How long does it take to finish an activity? This is accomplished by having each interviewee give three time estimates for each task that he is responsible for (minimum, most likely, and maximum).
- What are the probabilities of decision outputs?

Figure (2) shows the interrelationship between PM and CM processes and the minor processes underneath them. Appendix "B" stipulates full details of activities and decisions which PM and CM work orders must go through to be completed.

PM work orders are generated in batches once a week. The PM engineer prepares the weekly batch, allocates work orders according to each maintenance unit, and submits work orders to each unit whereby they go through the normal PM process. There are five maintenance units under the Head Quarter of Maintenance Division. Each unit is responsible for operating a certain type of service. Under each unit there are several workshops that vary in size from one unit to another. In this study only units that are related to building maintenance are included. The selected units are: (1) Electrical Repair Unit (ERU), (2) Air Condition Repair Unit (ACRU), and (3) Facility Maintenance Unit (FMU).

Figures B-1 and B-2 in appendix "B" show that both PM and CM processes contain several activities and decisions to complete one work order. The PM work orders are either closed after completion or transferred to the CM process. On the other hand, CM work orders enter the maintenance system by a request of a technician or a complaint from a customer. During the routine check, a technician who is performing PM work order can't continue the job because it requires major repairs. Thus, this PM work order will be converted into a CM work order or, in many cases, a CM dispatcher receives a complaint from a customer. This complaint will enter the maintenance system as a CM work order.

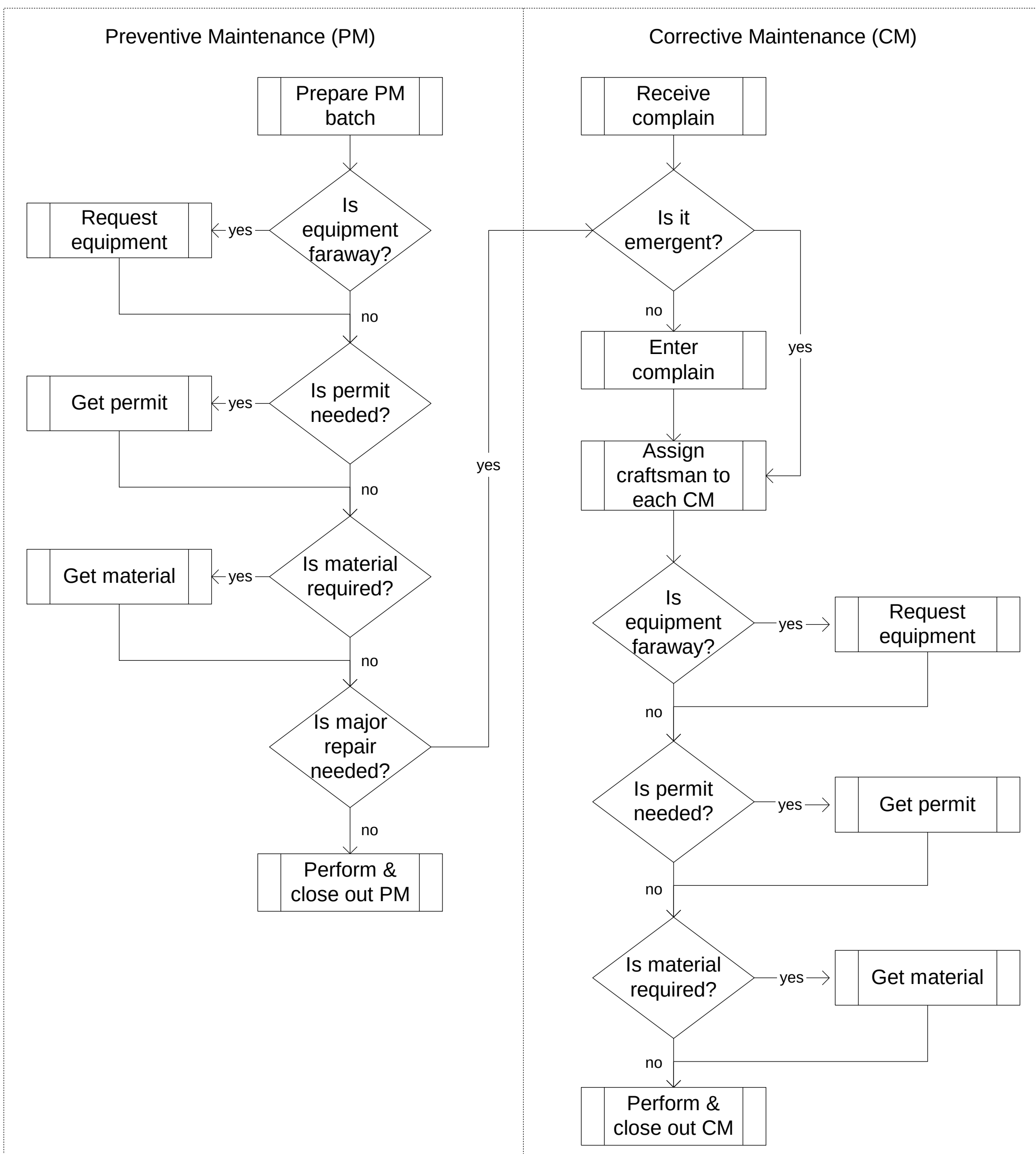
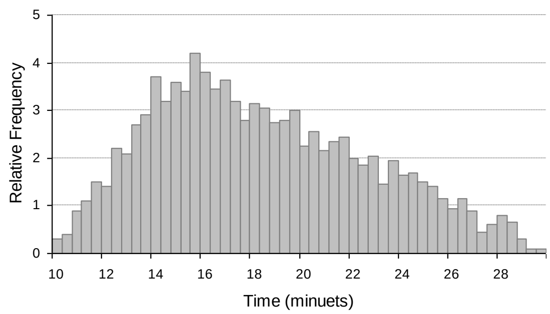


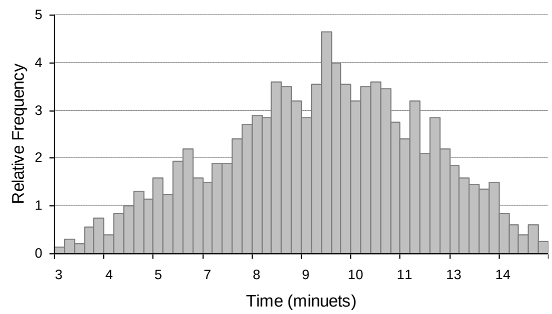
Figure 2: A macro process map for both preventive and corrective maintenance processes.

Collection of quantitative data:

Measuring activities' durations is one of the critical inputs to the validity of simulation models. It is apparent from the process maps presented in figures B-1 and B-2 of appendix "B" that both processes contain many activities. The activities' duration were estimated by experts who were asked to give three times (most likely, maximum, and minimum) for each activity as shown in Tables A-1 and A-2 of appendix "A". The sixth column in these tables presents the average for each activity that was calculated according to *Beta* distribution assumptions. The reason behind using *Beta* distribution is because of its adequacy and flexibility for most construction activities (AbouRizk *et al*. 1994 and Alkoc and Erbatur 1997). The average was useful in constructing the initial simulation model for verification purposes. The three time estimates were entered for each activity in the simulation model. Figure 3 (a & b) shows an example of one PM activity and another CM activity in which Extend+BPR converts such estimates into distributions. The same procedure was done for all activities. According to Cassady *et al.* (2001) probability distributions of activities in simulation models ensure a more realistic portrayal of real systems.



(a) PM Activity # 11- *Get Equipment* distribution



(b) CM Activity # 2- *Enter Complaint* distribution

Figure 3: Two examples of activities' time distributions in both PM and CM processes.

Another important piece of information is the percentage of occurrence of the decisions associated with both maintenance processes as shown in figure 2. Table 1 presents these decisions and their percentages of occurrence. For instance, a work permit is required whenever a WO is associated with hazardous equipment/material or it is located in a restricted area. This method of quantifying decisions is the one most used by several researchers (Hansen 1997, and Laguna and Marklund, 2005).

Table 1: Decisions with their percentage of occurrence.

Decision	Percent of Occurrence
Is equipment faraway?	10%
Is permit needed?	5%
Is material required?	21%
Is major repair needed?	11%

With respect to maintenance work orders, it is also important to know whether they are preventive or corrective and to what maintenance unit they belong to. Figure 4 summarizes the type and frequency of maintenance WO for 52 weeks which indicates that most work orders are handled by ACRU (45% of PM WO) while FMU got the least (14% of PM WO). These percentages are useful in simulating the flow and type of WO. In fact, modern simulation packages are object-oriented. The object in this case is the maintenance work order. Logic and issues related to the simulation model will be discussed in the next section.

Figure 4: Average weekly percentages with respect to type and frequency for both types of WOs.

Manpower cost is also another essential modeling input in order to compare the traditional system with the lean system. The cost of different technicians is gathered from SCECO personnel records. The cost of technicians varies according to their qualifications and years of experience. However, an average cost per hour was calculated so that it represents most technicians which is $15.2 per hour; on the other hand, the cost for a multi-skilled technician is $22.7 per hour (SCECO-Support-Facility, 1999).

The Maintenance Simulation Model:

To model maintenance processes, data collected in previous steps requires transfer into simulation notation. Each simulation package has its own form of activity notation or language which describes the precedence logic of the process network (Back and Bell, 1994). For this study, Extend+BPR was selected as the simulation modeling package because of its flexibility and adaptability in modeling lengthy complex processes (Abdulhadi, 1997 and Krahl, 2002).

Extend+BPR is an object-oriented simulation tool. In other literatures objects are referred to as “flow units” (Halpin and Riggs, 1992). The word “flow” implies that objects are dynamic and as they move in a process they may change their attributes or may gain more. Knowing what and how of an object is very crucial in building a credible accurate simulation model.

Objects vary according to the system they belong to. In the model presented in this study, the object is a maintenance work order whether preventive or corrective. Thus, the simulation models created for this study are designed to examine the flow of maintenance work orders for both PM and CM. This feature of object-oriented simulation packages allow the determination of how long each WO stays in a process that includes both processing time and waiting time. In doing so, one can accurately determine process efficiency.

Figures (5 and 6) show small portions of the maintenance model that was built on Extend+BPR. The most important part of any Extend+BPR model are the blocks, the libraries where blocks are stored, the dialogs associated with each block, the connectors on each block, and the connections between blocks (Krahl, 2002). A block specifies an action or process; it is used to represent an activity, an event or a function of a model. Some blocks may simply represent sources of information. Others may modify information as it passes through them. Information comes into the block and is processed by the program that is embodied in the block. The block then transmits information out of the block to the next block in the simulation.

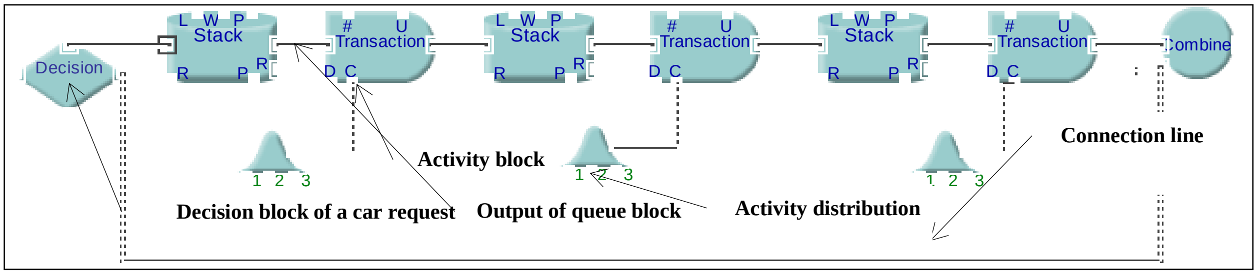


Figure 5: Portion of the maintenance simulation model that mimics the car request activities.

Moreover, almost all blocks in Extend+BPR have input and output connectors, the small squares attached to the side of each block. Input and output connectors are usually pre-defined; their function is known in advance. Connection lines are used to hook blocks together; they show the flow of information from block to block through the model (Imagine that 2000).

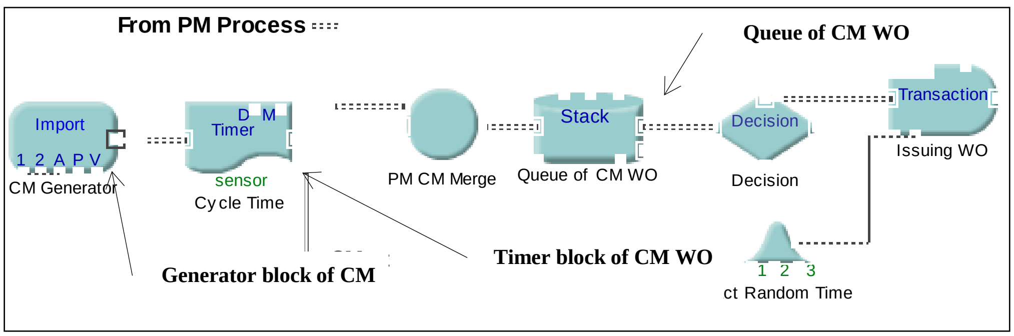


Figure 6: Another portion of the maintenance simulation model that mimics issuance of CM WO.

A successful modeling is totally dependent on the development of a base-line model that accurately mimics the present work flow process and the interrelationships among various tasks (Ardhaldjian and Fahner, 1994). In this study the base-line model is referred to as the traditional model. Before experimenting with simulation to evaluate the effect of MST, it is necessary to verify and validate the traditional models. Verification basically implies examining two questions (Back and Bell, 1994), which are:

1. Does every transaction go where it is suppose to go under every condition? For example, in corrective maintenance model a technician can't start a work order unless there is a complaint.

2. Does every transaction do what it is suppose to do under every condition? This is very crucial in almost all simulation models because changes to the traditional model are expected. In fact, Chisman (1992) stated that the true benefit of simulation modeling is the ability to explore what-if analysis with respect to a defined process.

However, verification does not guarantee that the model is valid (i.e., accurately represents the actual system) (Houshyar and Nuila, 1994). A comparison between the model outcomes and the data gathered from both processes on site was made as shown in table 2 to ensure the validity of the model.

Table 2 shows two sets of data, actual and empirical, for the total cycle time to close out one work order of either PM or CM and the number of completed work orders per week. The actual data was gathered from previous records for both processes whereas empirical data was gathered from simulation models. Notice how close the two sets of data which proves that the simulation models are valid and ready for evaluation.

Table 2: Comparing the outcomes of the traditional model with the actual data.

	Cycle Time (hours)		Throughput (WO/week)	
	Actual	Empirical	Actual	Empirical
PM	16	15	110	115
CM	22	20	80	76

The verified-validated traditional model was used as a reference point to measure and compare the impact of MST on maintenance processes. The concept of MST implied some changes to both PM and CM processes. By looking into process maps presented in figures B-1 and B-2 PM activities with numbers 3 (*Segregate PM sheets*), 6.1 (*Assign PM to specific unit*), and 6.2 (*Assign PM to craftsmen*) are not always required because the superintendent can most of the time assign work orders directly. Similarly, CM activities with numbers 3 (*Distribute to units*) and 5 (*Assign CM to craftsmen*) are not required either. Running the simulation model with these changes and being capable of meeting most maintenance orders due to MST, led to a leaner system that is going to be discussed further in the coming section.

RESULTS AND DISCUSSIONS

Table (3) compares results of both traditional and lean maintenance models in terms of cycle time, labor cost, crew utilization and throughput. One may notice the remarkable improvement gained by implementing the concept of MST. Regarding the PM process, there is a 68% reduction in cycle time and 56% reduction in cost. In terms of crew utilization and throughput the PM process improved by 45% and 27%, respectively. Results with respect to the CM process are encouraging as well, but, they are less than those in the PM process. The difference in improvement is due to the fact that the maintenance policy in SCECO gave more priority to PM work orders. These improvements are attributed to the high response to work orders where they wait for a short time in the maintenance process. The role of the maintenance superintendent and the activities associated with him are markedly reduced in the lean system.

Table 3: Comparing results of both traditional and lean maintenance models.

	Cycle Time (hours)		Labor Cost ($/WO)		Utilization		Throughput (WO/week)	
	Traditional	Lean	Traditional	Lean	Traditional	Lean	Traditional	Lean
PM	15	4.8	295	129	42	87	110	140
CM	22	9.5	420	201	42	87	80	98

Figure 7 compares the crew utilization of the two processes where one can see the remarkable difference between the two. The utilization rate of the traditional maintenance in figure 7 is the average of the three units (ERU, ACRU, FMU). Almost 87% of the technician time in the lean system is spent on performing maintenance work orders. One may notice how steady the lean utilization curve is along the simulation run time; it has also gained a high rate of utilization right from the beginning as opposed to the traditional utilization curve. The utilization rate is the same in both processes as all technicians are responsible for both types of work orders. The enhanced utilization of technicians contributed to the increase in throughput where 140 PM WO/week and 98 CM WO/week are accomplished. This is comparable to the results of Mjema study (2002) who found a 91% improvement of utilization rate.

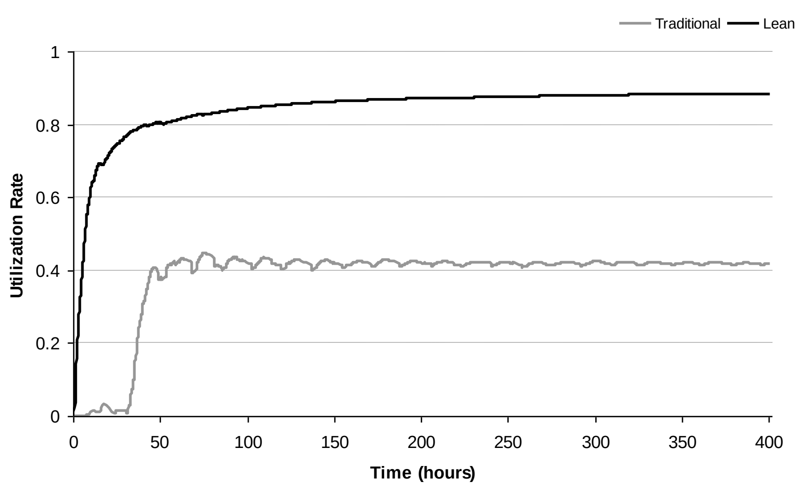


Figure 7: Comparison of technician utilization of the two processes.

On the contrary, crew utilization in the traditional maintenance process is very low. It is as low as 34% in facility maintenance unit (FMU) as shown in figure 8. This is because the work orders have to go through long paper work before they get assigned to a specific maintenance unit. Once these work orders reach their units, the superintendent checks the availability of his craftsmen who may be busy in other work orders. Another reason that led to low utilization is the type of work orders that may vary according to seasons. For instance, in summer there is more demand on A/C repairs and checkups than in winter. This necessitates a responsive and adaptable system that can

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meet most maintenance work orders. One way is to provide more skilled technicians who can handle most maintenance services. By doing so, maintenance processes will be more flexible; being flexible is one of the major indicators of proactive management (Organ *et al.*, 1997), and this is another advantage of employing MST.

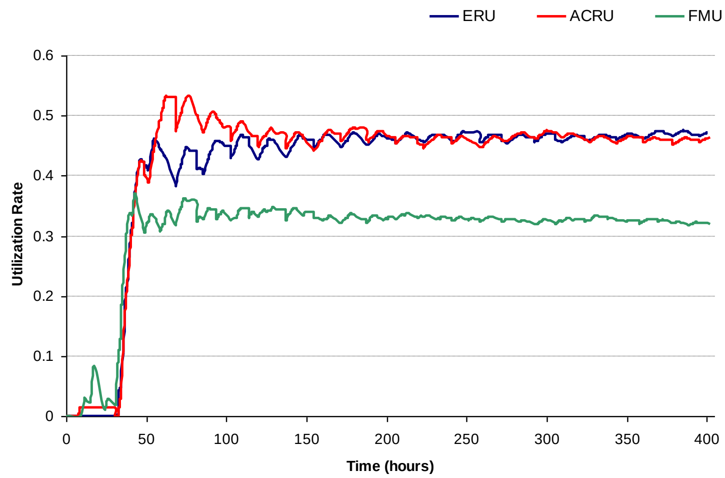
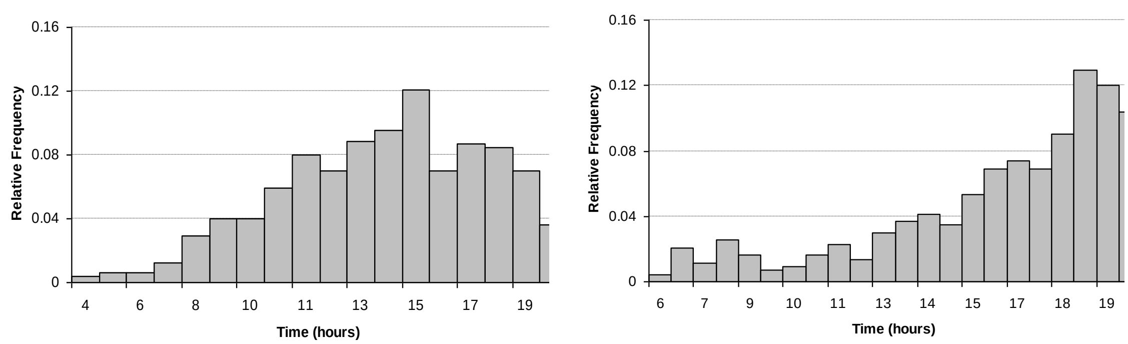


Figure 8: The different technician utilization rates in the traditional maintenance model.

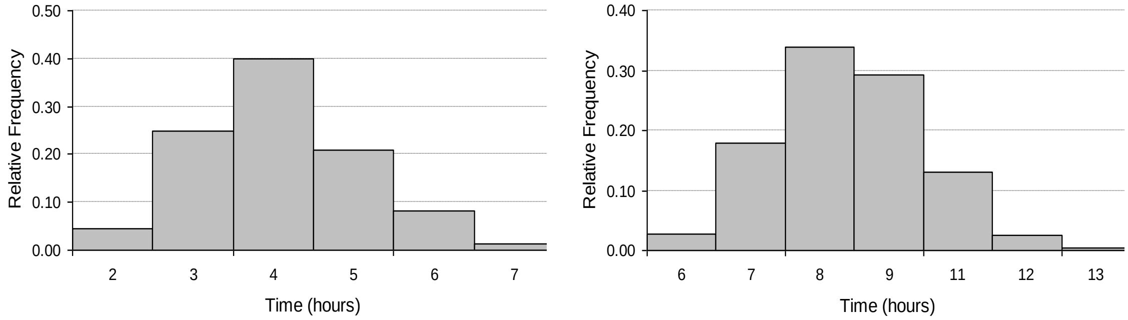
Figures 9 and 10 present cycle time distribution of work orders for both PM and CM processes in the traditional and lean systems. Again this shows the magnitude of the potentiality of MST. The work orders in the traditional system take longer to be completed where it takes an average of 15 hours compared to 4 hours in the lean system. Besides, the long time of WO in the traditional system one may notice the huge variability in both distributions as shown in Figure 9. There is a 16-hour difference in the traditional preventive maintenance process, which is almost the same in the corrective maintenance process. The huge variability indicates a weakness in the existing process. In fact, Narayan (1998) concluded that process variability is a major source of cost increase, which is the case in the traditional process.



(a) Traditional PM cycle time distribution

(b) Traditional CM cycle time distribution

Figure 9: Cycle time distribution for 2000 runs of the traditional maintenance process.



(a) Lean PM cycle time distribution **(b) Lean CM cycle time distribution**

Figure 10: Cycle time distribution for 2000 runs of the lean maintenance process.

The presented case study is huge where there are many buildings of various functions and uses. The amount of maintenance work orders is expected to be huge and diverse as well. In situations like this, the MST concept may work well. In other situations where work orders are not as frequent/diverse as in this case stud, an MST concept may not be very effective. The cost-benefit ratio of a multi-skilled technician may not be significant. This requires further investigation on the factors that influence the potentiality of MST.

The number of multi-skilled technicians modeled in this study was almost one third the number of traditional technicians. This affirms another advantage of MST concept to the construction industry that is facing more demands and challenges to be faster and more productive, and to meet the shortage in skilled laborers. To overcome these demands and challenges, there is a need to invest more in training laborers in order to improve their skills in different services. This would enhance one major input, which is human resources, to construction/maintenance processes by adding more value to their outcomes and eventually to the final product or service.

Towards Leaner Processes:

The improvement gained by the lean concept of MST was relative to the traditional maintenance process practiced by SCECO, which contained huge amount of waste. Looking back, figure 10 (a and b) shows that the lean maintenance model has a better performance, but, work orders still go through variable time. It is not as variable as the ones in the traditional maintenance model. However, waste still exists in the lean model. This is because the emphasis of the current study is on multi-skilled technicians where the process stayed almost the same as in the traditional process. This proves that lean theory requires a comprehensive view of implementation rather than focusing on one part of it, which supports the conclusion of Bhasin and Burcher (2006).

Applying one or few aspects of lean theory will not guarantee full waste elimination. To be specific focusing on people, processes and technologies has a great impact on leading to leaner processes. Understanding a process and improving it is a key principle in lean theory. Waste and its sources are manifested more when management has a clear picture of its process, that is; non-value-adding activities, queues and decisions and their paths can be identified through process maps. In this study a process mapping technique was used to understand the existing maintenance process and be able to build a simulation model. Identifying and eliminating wastes associated with activities in the studied process were beyond the scope of this study.

Focusing on technologies also has a significant impact on leading to leaner processes. Many of the activities in the maintenance process of the case study can be done electronically. In doing so, some of the activities will be eliminated or the time needed to complete them is reduced which will expedite information transfer and enhance communication. For example, activities 8, 9 and 10 in the PM process can be mainly done electronically with minimal paper work, that is; work permits can be sent electronically to the superintend without the presence of a technician. While the technician awaits his superintendent's approval, he can perform other work orders that will add value to the maintenance system. Indeed, integrating people, processes, and technologies is essential in adopting a system view of the lean theory.

CONCLUSION

This study evaluated the benefits of MST to a maintenance process of a leading company (SCECO) using object-oriented simulation package (Extend+BPR). Simulating the concept of MST led to significant improvement in terms of cycle time, labor cost, utilization and throughput. The average time and cost to complete one PM work order were reduced by 68% and 56%, respectively. Also, technician utilization and productivity improved by 45% and 27%, respectively. The performance of the PM process was better than that of the CM process because the former process was given more priority. Thus, the balance between the two processes requires more attention that may be achieved in future studies.

This study focused on people as one aspect of the triad of lean theory (people, processes and technologies) at a production level of a maintenance process. Extending maintenance technicians' breadth and depth of their skills will have a positive impact on their performance as well and eventually will add value to the final product or service. However, it is extremely important to look into lean production theory as a system of people, processes and technologies to get the best out of it.

REFERENCES

Abdulhadi, Nader H. (1997). Simulation As a Tool for Re-engineering Construction Processes. Unpublished Ph.D. Dissertation, Department of Civil, Environmental and Architectural Engineering, University of Colorado-Boulder, USA

AbouRizk, S., Halpin, D. and Wilson, J. (1994). Fitting Beta Distribution Based on Sample Data. Journal of Construction Engineering and Management, Vol. 120, No. 2, pp. 288-305.

Alarcon, Luis F. (1997). Modeling Waste and performance in Construction Lean Construction, edited by Luis Alarcon, Balkema, Rotterdam, The Netherlands

Al-Arjani, A. (2002). Type and Size of Project Influence on Number of Bidders for Maintenance and Operation Projects in Saudi Arabia. International Journal of Project Management, 20, 279-287.

Alkoc, E. and Erbatur, F. (1997). Productivity Improvement in Concreting Operations Through Simulation Models. Building Research and Information, Vol. 25, No. 2, pp. 82-91.

Al-Sudairi, A. (2007). Evaluating the Effect of Construction Process Characteristics to the Applicability of Lean Principles. Journal of Construction Innovation, Vol. 7, No. 1, pp 99-121.

Ardhaldjian, R. and Fahner, M. (1994). Using Simulation in the Business Process Reengineering Effort. Industrial Engineering, July, pp. 60-61.

Back, W. Edward and Bell, Lansford (1994). Quantifying Benefits of Electronic Technology Applied to Bulk Materials Management. Published by Construction Industry Action Group

Bhasin, S. and Burcher, P. (2006). Lean Viewed as Philosophy. Journal of Manufacturing Technology Management, Vol. 17, No. 1, pp. 56-72.

Carley, L., Goodrum, P., Haas, C. and Borcherding, J. (2003). Experience With Multiskilling Among Non-Union Craft Workers in US Industrial Construction Projects. Engineering Construction and Architectural Management, Vol. 10, No. 6, pp. 374-381.

Cassady C., Pohl, E. and Murdock, W. (2001). Selective Maintenance Modeling for Industrial Systems. Journal of Quality in Maintenance Engineering, Vol. 7, No. 2, pp. 104-117.

Chisman, James (1992). Introduction to Simulation Modeling Using GPSS/PC, Prentice Hall, Englewood Cliffs, NJ, USA

Duffuaa, S., Ben-Daya, M. and Al-Sultan, K. (2001). A Generic Conceptual Simulation for Maintenance Systems. Journal of Quality in Maintenance Engineering, Vol. 7, No. 3, pp. 207-219.

Farrar, J., AbouRizk, S., and Mao, X. (2004). Generic Implementation of Lean Concepts in Simulation Models. Lean Construction Journal, Vol. 1, pp 1-23.

Forza, C. (1996). Work Organization in Lean Production and Traditional Plants. International Journal of Operations, Vol. 16, No. 2, pp. 42-62.

Halpin, D., and Riggs, L. (1992) Planning and Analysis of Construction Operations. John Wiley & Sons, Inc

Hansen, G. (1997). Automating Business Process Reengineering: Using the Power of Visual Simulation Strategies to Improve Performance and Profit, Prentice Hall PTR, New Jersey, USA.

Horner, R., El-haram, M. and Munns, A. (1997). Building Maintenance Strategy: a New Management Approach. Journal of Quality in Maintenance Engineering, Vol. 3, No. 4, pp. 273-280.

Houshyar, A. and Nuila, V. (1994). Well-Designed Simulation: A Tool for Superior Manangement, Part1. International Journal of Modeling And Simulation, Vol. 14, No. 3, pp 129-133.

Imagine that, Inc. (2000). Creator of the Extend family of simulation software for discrete event and continuous simulation, San Jose, CA, USA.

Ip, W., Lee, W., Yung, K. and Yam, R. (2000). SCADA in an Integrated Maintenance Management System. Journal of Quality in Maintenance Engineering, Vol. 6, No. 1, pp. 6-19.

Koskela, L. (1999). Management of Production in Construction: A Theoritical View. Proceedings 7th Ann. Conf. Intl. Group for Lean Construction, IGLC-7, edited by Iris Tommelein, University of California, Berkeley, California, USA.

Krahl, D. (2002). The Extend Simulation Environment. Proceedings of the 2002 Winter Simulation Coference, E. Yucesan, C. Chen, J. Snowdon, and J. CHarnes, eds., pp. 205-213.

Laguna, M. and Marklund, J. (2005). Business Process Modeling, Simulation and Design. Prentice Hall, Upper Saddle River, New Jersey, USA.

Lobo, Y. and Wilkinson (2008). New Approaches to Solving the Skills Shortages in the New Zealand Construction Industry. Engineering Construction and Architectural Management, Vol. 15, No. 1, pp. 42-53.

Mathaisel, D. (2005). A Lean Architecture for Transforming the Aerospace Maintenance, Repair and Overhaul (MRO) Enterprise. International Journal of Productivity and Performance Management, Vol. 54, No. 8, pp. 623-644.

Mjema, E. (2002). An Analysis of Personnel Capacity Requirement in the Maintenance Department by Using a Simulation Method. Journal of Quality in Maintenance Engineering, Vol. 8, No. 3, pp. 253-273.

Narayan, V. (1998). The Raison *D'etre* of Maintenance. Journal of Quality in Maintenance Engineering, Vol. 4, No. 1, pp. 38-50.

Oral, E., Mistikoglu, G. and Eedis, E. (2003). JIT in Developing Countries: A Case Study of the Turkish Prefabrication Sector. Building and Environment, Vol. 38, pp. 853-860.

Organ, M., Whitehead, T. and Evans, M. (1997). Availability-Based Maintenance within an Asset Management Programme. Journal of Quality in Maintenance Engineering, Vol. 3, No. 4, pp. 221-232.

Parida, A. (2007). Study and Analysis of Maintenance Performance Indicators (MPIs) for LKAB. Journal of Quality in Maintenance Engineering, Vol. 13, No. 4, pp. 325-337.

Pintelon, L., Pinjala, S. and Vereecke, A. (2006). Evaluating the Effectiveness of Maintenance Strategies. Journal of Quality in Maintenance Engineering, Vol. 12, No. 1, pp. 1-20.

Salem, O., Solomon, J., Genaidy, A. and Luegring, M. (2005). Site Implementation and Assessment of Lean Construction Techniques. Lean Construction Journal, Vol. 2, No. 2, pp. 1-21.

SCECO-Support-Facilities (1999). Business Process Improvement. A Technical Report Published by SCECO-East, Dammam, Saudi Arabia.

Soderholm, P., Holgren, M. and Klefsjo, B. (2007). A Process View of Maintenance and Its Stakeholders. Journal of Quality in Maintenance Engineering, Vol. 13, No. 1, pp. 19-32.

Taj, S. (2005). Applying Lean Assessment Tools in Chinese Hi-Tech Industries. Management Decision, Vol. 43, No. 4, pp. 628-643.

Wang, C. and Hwang, S. (2004). A Stochastic Maintenance Management Model with Recovery Factor. Journal of Quality in Maintenance Engineering, Vol. 10, No. 2, pp. 154-164.

Womack, J, and Jones, D. (1990). *The Machine that Changed the World.* Rawson, New York, USA.

Womack, J. and Jones, D. (1996). Lean Thinking: Banish Waste and Create Wealth in Your Corporation. Simon & Schuster, New York.

APPENDIX (A): TIME ESTIMATES FOR MAINTENANCE ACTIVITIES

Table A-1: Time estimates in minutes of Preventive Maintenance activities.

No.	Task	Minimum	Most likely	Maximum	Average
1	Assign no. to each work order	5	8	12	8.17
2	Check printed PM sheet	4	8	10	7.67
3	Segregate PM sheet	2.5	4	7	4.25
4	Print PM work orders	5	10	15	10.00
5	Review PM schedule	3	7	11	7.00
6	Assign PM to specific units/craftsman	2	4	7	4.17
7	Get required tools	10	15	30	16.67
8	Fill out a request	10	15	30	16.67
9	Get foreman approval	10	18	25	17.83
10	Get approval of superintendent	11	20	30	20.17
11	Get equipment	10	15	30	16.67
12	Fill out a permit	30	45	60	45.00
13	Evaluate and sign permit	8	10	15	10.50
14	Material acquisition	3	30	90	35.50
15	Check actual PM work	10	11	15	11.50
16	Perform actual PM work	60	120	240	130.00
17	Fill out PM report	4	7	10	7.00
18	Review PM work	4	6	7	5.83
19	Close PM work order	2	3	4	3.00

Table A-2: Time estimates in minutes of Corrective Maintenance activities.

No.	Task	Minimum	Most likely	Maximum	Average
1	Receive complaint	1	2	3.5	2.08
2	Enter complaint	3	10	15	9.67
3	Distribute to units	2	3	5	3.17
4	Review CM schedule	2	3	5	3.17
5	Assign CM to craftsman	2	3	5	3.17
6	Get tools	10	15	30	16.67
7	Fill out a request	2	3	4	3.00
8	Get foreman’s approval	2	5	7	4.83
9	Obtain Approval of superintendent	2	3	6	3.33
10	Get equipment	10	15	30	16.67
11	Fill out work permit	8	10	15	10.50
12	Review and sign permit	30	45	60	45.00
13	Material acquisition	30	45	90	50.00
13	Check actual CM work	10	11	15	11.50
14	Perform actual CM work	30	60	120	65.00
15	Sign CM by requester	1	3	5	3.00
16	Fill out CM report	4	7	10	7.00
17	Review by foreman	5	10	20	10.83
18	Close CM work order	2	3	7	3.50

APPENDIX (B): DETAILED MAINTENANCE PROCESSES MAPS

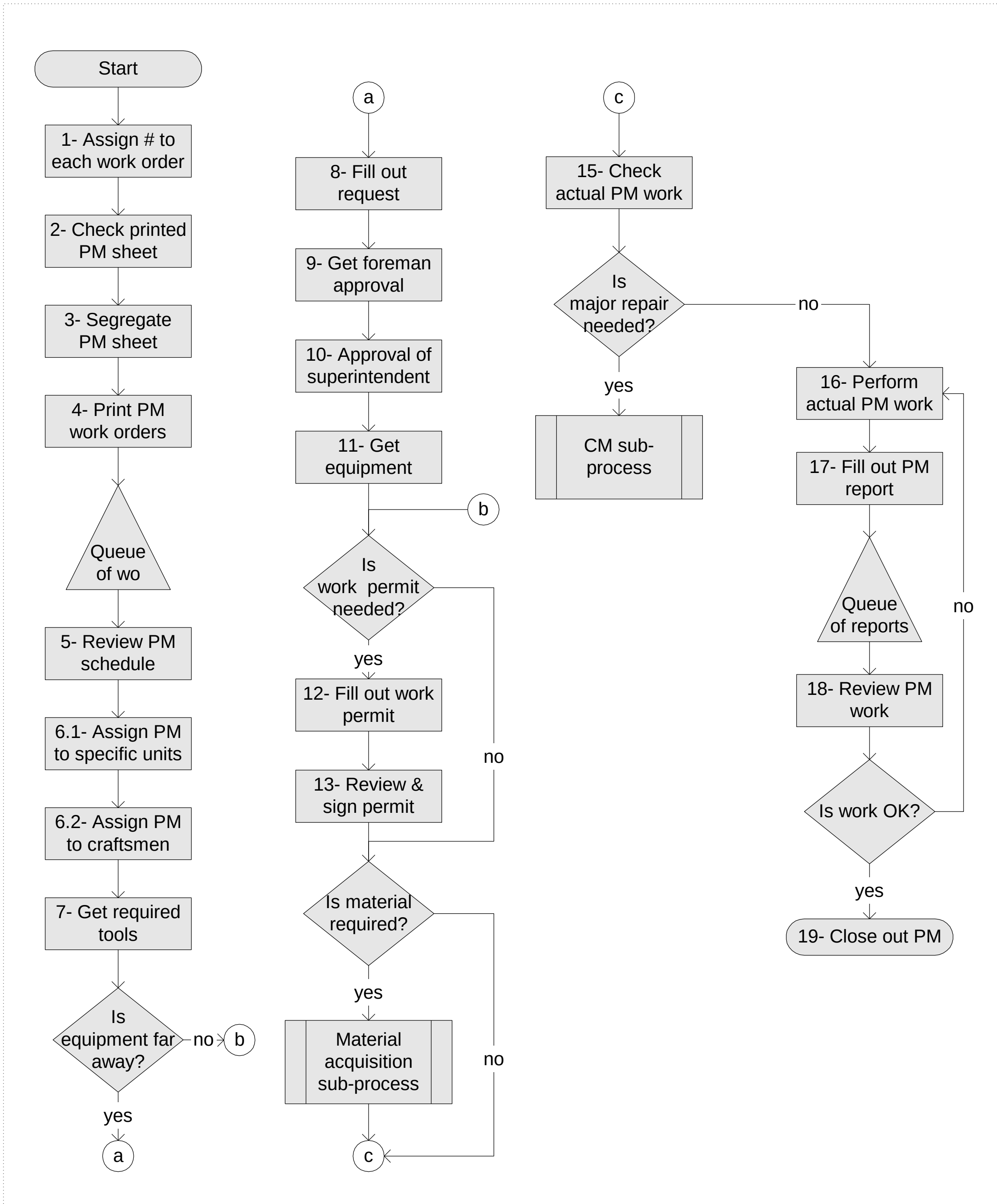


Figure B-1: Preventive maintenance micro process map.

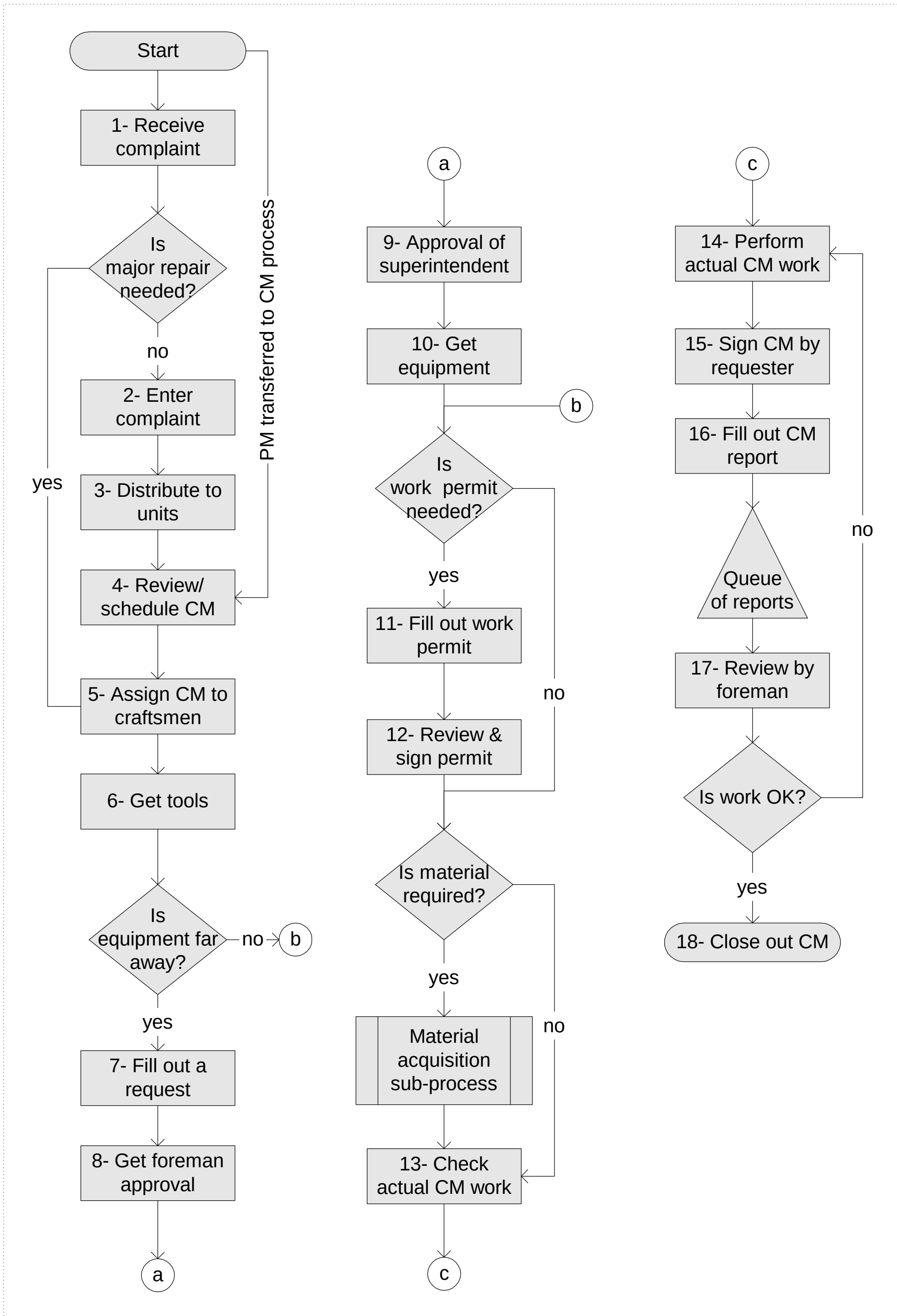


Figure B-2: Corrective maintenance micro process map.