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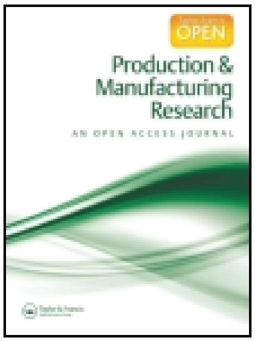

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Lean thinking for a maintenance process

Sherif Mostafa[a]*, Sang-Heon Lee[b], Jantanee Dumrak[c], Nicholas Chileshe[a] and Hassan Soltan[d]

[a]*School of Natural and Built Environments, University of South Australia, Adelaide 5000, Australia;* [b]*School of Engineering, University of South Australia, Mawson Lakes 5095, Australia;* [c]*Global Management Program, Torrens University Australia, Adelaide, SA 5000, Australia;* [d]*Production Engineering and Mechanical Design Department, Faculty of Engineering Mansoura University, Mansoura 35516, Egypt*

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The maintenance process shares significant operating costs in an organisation. Lean thinking can be incorporated into maintenance activities through applying its principles and practices/tools. Lean maintenance (LM) is a prerequisite for lean manufacturing systems. This research proposes a new structure for LM process based on a systematic literature review of a significant number of related articles that were published on LM. The process structure is designed based on the five lean principles to guide and support organisations to pursue maintenance excellence. This study establishes a scheme for LM tools that are structured into 2 level 4 bundles and 26 lean practices/tools and develops a House of Waste (HoW) to demonstrate the association between maintenance wastes and the LM tools. With a successful accomplishment of the proposed scheme, the performance of a maintenance department can create more improvement opportunities over time to reach the maintenance excellence status.

Keywords: total productive maintenance (TPM); lean maintenance; maintenance wastes and value stream mapping; lean maintenance tools; House of Waste (HoW)

1. Introduction

Maintenance function becomes a significant contributor towards to achieve strategic objectives of an organisation in today's competitive markets (Fraser, 2014). The maintenance process is to serve the production facilities of high productivity. It comprises planned and unplanned actions carried out to retain a physical asset to the acceptable operating conditions (Faccio, Persona, Sgarbossa, & Zanin, 2014). Maintenance aims at increasing the value of the reliability, safety, availability, and quality of an asset (e.g. production plant, equipment, or building) with acceptable economical costs (Márquez, 2007). Over the last decades, the maintenance has been considered as a necessary evil from the organisational management as the maintenance operation is limited to corrective functions that are usually executed under the emergency situations such as machine breakdown. However, this practice is no longer acceptable since the role of maintenance has been recognised as a strategic element of revenue generation for organisations. The maintenance with role creates a significant impact on some critical elements in production plants such as product quality, safety requirements, and operating budget levels (Khazraei & Deuse, 2011).

*Corresponding author. Email: Sherif.Mostafa@mymail.unisa.edu.au

The cost of maintenance activities could be ranged from 15 to 70% of the total production costs (Fraser, 2014; Pinjala, Pintelon, & Vereecke, 2006). This is the second largest part, after energy costs, of the operational budget. In the United States, the estimated cost of maintenance increased from \$200 billion in 1979 to \$600 billion in 1989 (Bevilacqua & Braglia, 2000). Maintenance activities account for an average 28 per cent of the total cost of finished goods (Blanchard, 1997). One of the reasons for such significant portion of maintenance of the total operation cost is that the machinery has become highly automated and technologically very complex. For example, usually, the modern operation systems depend on sensor-driven management systems that provide alerts, alarms, and indicators. Consequently, maintenance costs are expected to be even higher in future. Generally, the maintenance costs are proportional to the downtime (DT). The DT is the time interval when equipment/system is down for maintenance until it is back to the normal working conditions (Tinga, 2013). The increased DT is caused by the non-value added (NVA) activities or wastes within the entire maintenance process. One of waste elimination strategies is the application of lean thinking in all activities between suppliers and customers (value stream). Integrating lean thinking in maintenance is known as lean maintenance (LM). Baluch, Abdullah, and Mohtar (2012) emphasised that LM is prerequisite for success of a lean manufacturer as it provides a holistic approach to the function of maintenance. In general, the lean integration in any process is carried through adopting lean principles which begins with specifying the customer value (Bhasin, 2015). In the maintenance environment, any maintenance service could be considered as a final intangible product. The service is provided to a customer which, in this case, could be assumed as an asset (e.g. production line). Therefore, it is essential to identify the value from the asset perspective which can be improving its availability and reliability through efficient maintenance. Then, mapping the maintenance value stream which fundamentally consists of all the collective activities to deliver the maintenance service. Later, improving the maintenance value stream by abolishing the waste which assist in minimising the lead time (in this case is DT).

Investigation into the applicability of lean principles in maintenance in the existing research is still at a marginal level. Davies and Greenough (2010) emphasis on the necessity for more researches to apply lean principles to maintenance operations. Ghayebloo and Shahanaghi (2010) formulate a multi-objective decision-making (MODM) model that can determine the minimal level of maintenance requirements (i.e. labour and spare parts) which satisfies expected reliability level with the use of the lean concept. Tendayi and Fourie (2013) use a combined approach of quality function deployment (QFD) and analytic hierarchy process (AHP) to evaluate the importance of a set of maintenance excellence criteria and prioritise the lean tools against these criteria. Soltan and Mostafa (2014) introduce a framework for measuring maintenance strategies based on lean and agile components, i.e. waste removal and responsiveness. The study of McCarthy and Rich (2004) discussed lean total productive maintenance system (or lean TPM) which conceptualises the application of lean-specific techniques in TPM. The system is focused on maintaining equipment in its optimal operational state and continually improving its productivity. However, an integrative structure of lean thinking or lean TPM (e.g. principles, practices/tools, waste identification, and value stream mapping (VSM)) within the maintenance activities has not been fully established. This provides an opportunity for this study to develop and propose a process for lean thinking to be integrated to the maintenance operation. The process is formulated according to the hypothesis of Womack and Jones (2003) stating that lean principles can be applied to any sector.

This study carried out a systematic literature review following Denyer and Tranfield (2009) approach. The review was conducted to identify and understand the existing literature on LM and evaluate contributions and summarise knowledge, thereby, identifying potential directions of future research. The grand electronic databases were explored to gather the literature on LM. A total of 43 related articles published between 2000 and 2014 have been included in this study.

This study is organised as follows. Section 2 provides an overview on maintenance and lean manufacturing concepts. Sections 3 and 4 demonstrate the aim, objectives, and methodology of the proposed research. Section 5 discusses the LM and LM practices/tools. In Section 6, a LM process is proposed with the discussion of the five stages of the lean process in maintenance and introduction of the LM scheme including four bundles and 26 lean tools. The section also demonstrates the relationships between maintenance wastes and lean tools using House of Waste (HoW). Section 7 highlights benefits of the proposed LM process and Section 8 concludes the study with some directions of future research.

2. Maintenance and lean manufacturing

2.1. Lean manufacturing

The word lean in manufacturing means the efficient use of the available resources by cutting the NVA activities or wastes (Carrasqueira & Machado, 2008). Lean manufacturing represents a collection of tools that work together synergistically to create a streamlined, high-quality system that produces finished products at the same pace of the customer demand (Shah & Ward, 2007). Waste in lean manufacturing is defined as any activities that add cost to a product/service without adding values from a customer's perspective. It may be classified to three major types: unobvious waste, less obvious waste, and obvious waste (Hopp & Spearman, 2004). De Treville and Antonakis (2006) list examples of obvious waste as unnecessary inventory, unneeded processes, excessive set-up times, unreliable machines, and rework. They also argue that the less obvious waste occurs due to the various reasons such as process times, delivery times, yield rates, staffing levels, and demand rates.

In recent decades, lean system is gaining a momentum across different industrial sectors. It has been originally started as Toyota production system which describes the manufacturing philosophy of Toyota Motor Corporation (Dombrowski & Malorny, 2014; Holweg, 2007; Womack & Jones, 2003). This lean system has been successfully extended to service industries, such as maintenance service, retail banking, airlines, restaurants, public sector, education, food, and hospitals (Burgess & Radnor, 2013; George, 2003; Pedersen & Huniche, 2011; Resta, Powell, Gaiardelli, & Dotti, 2015; Smith & Hawkins, 2004; Thirkell & Ashman, 2014; Zarei, Fakhrzad, & Jamali Paghaleh, 2011). As an example, in the health care sector, hospitals achieved high-quality health care outcomes (e.g. recorded lower 30-day mortality rates) by applying lean management practices (McConnell, Lindrooth, Wholey, Maddox, & Bloom, 2013). Clearly, the implementation of lean concept in diverse sectors proves to be true Womack and Jones (2003) hypothesis stating that lean principles can be transferred to any organisation. They coined this process as lean thinking which refers to the thinking process of lean inside an organisation and its extended supply chain. This means that within the same organisation, lean thinking should be extended from the shop floor or production level to other areas such as maintenance department. The key behind this lean thinking is that service/maintenance departments and production processes are inseparable and complement each other to sustain the competitive edge of an organisation.

2.2. Maintenance strategies

Maintenance includes all activities required to keep an asset at maximum operating condition. The activities are usually carried out according to a certain maintenance strategy. The maintenance strategies may have developed accordingly with the development of manufacturing systems (Shahin, Shirouyehzad, & Pourjavad, 2012). In the early days, maintenance had been mainly concentrated around corrective maintenance, for example, repairs and replacements were conducted when needed with no optimisation strategy and there was no or little consideration of the DT. More recently, maintenance became a full-scale function, instead of a sub-function of the whole production operation. Today, maintenance management becomes a complex function, encompassing technical and management skills, while still requiring flexibility to cope with the dynamic business environment (Lee & Wang, 2008). Maintenance strategies have gradually changed from preventive maintenance (PM) (including condition-based maintenance (CBM) and time-based maintenance (TBM) to design-out maintenance (DOM) and total productive maintenance (TPM) as demonstrated in Figure 1.

The classification of the maintenance strategies shown in Figure 1 is based on the time of maintenance activities and failure that requires maintenance (Potes Ruiz, Kamsu Foguem, & Grabot, 2014). The maintenance activities are only performed after the failure occurrence in the corrective maintenance strategy. Whereas, in the PM, the intervention of maintenance activities is conducted before the failure occurrence. Maintenance strategies have been diversely used in the existing literature using similar terms such as preventive, predictive, planned, corrective, and TPM. The most common three maintenance strategies are discussed below.

2.2.1. Corrective maintenance

Corrective maintenance is known as failure-based maintenance, emergency maintenance, fire-fighting maintenance, or breakdown maintenance as the concept of corrective

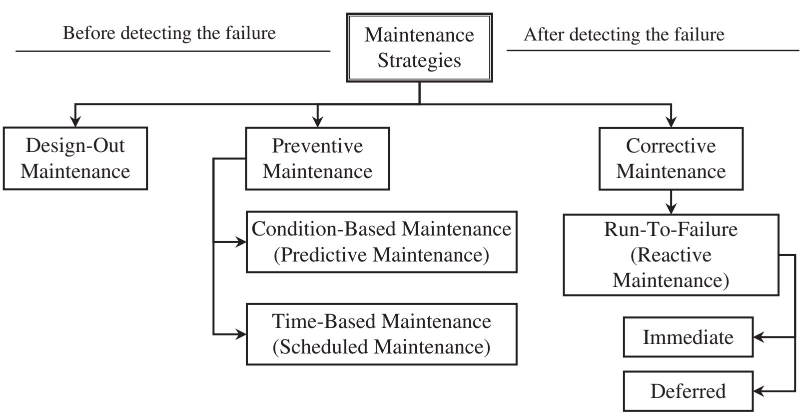

Figure 1. Types of maintenance strategies.

maintenance strategy is based on fix-it when broke (Márquez, 2007). Corrective maintenance is a conventional maintenance strategy appeared early in the industry. It has been employed in maintenance operations due to knowledge shortage on the equipment failure behaviours (Waeyenbergh & Pintelon, 2002). Corrective maintenance can be carried out immediately or deferred by appropriate maintenance technicians whom are contracted to assess the situation and fix the repairs. In situations where the failure is not critical (i.e. plenty of DT is available) and the values of the assets are not of a great concern, the corrective mode of maintenance may prove to be an acceptable option. However, the market competition, environmental and safety issues force the maintenance managers to search for more efficient maintenance strategies besides the corrective maintenance (Shahin et al., 2012).

2.2.2. Preventive maintenance

PM is carried out according to prescribed criteria. It intends to reduce the probability of failure or the degradation of the functioning of an item (Fouladgar, Yazdani-Chamzini, Lashgari, Zavadskas, & Turskis, 2012). PM can be divided into TBM and CBM. In TBM, the maintenance activities are performed based on fixed operating time interval or number of output units without considering the current condition state of the item. On the other hand, CBM is based on performance and/or parameter monitoring (e.g. corrosion and electric current monitoring, lubricant and vibration analysis, leak and crack detection, and ultrasonic testing) (Al-Najjar & Alsyouf, 2003; Khazraei & Deuse, 2011). CBM could be described as a process that integrates technology and human skills using a combination of all available diagnostic and performance data, maintenance history, operator logs, and design data to determine the likelihood of a potential failure. As a result, CBM requires a high initial cost to acquire and install the necessary sensors as well as to monitor technology (Hellingrath & Cordes, 2014; Nezami & Yildirim, 2013).

2.2.3. Design-out maintenance

DOM focuses on improving the design of a product in order to eliminate the cause to maintenance. DOM makes maintenance easier during the life cycle of a product (Waeyenbergh & Pintelon, 2004). DOM is based on the successive design corrections derived from the maintenance knowledge. It is appropriate for items with high maintenance cost, which arises because of defective design or operation outside design specifications. The DOM concept is used in some parts of motor vehicles such as permanent bearing (bearing using solid lubricant and permanently sealed) (Gopalakrishnan & banerji, 2013).

2.3. TPM and lean thinking

TPM is a concept developed in Japan, which could be defined as a productive maintenance that involves total participations meaning all employees across the whole levels of the operational hierarchy (Cua, McKone, & Schroeder, 2001; Jasiulewicz-Kaczmarek, 2013). It attempts to eliminate any losses in equipment and production efficiency through active team-based participation. Waeyenbergh and Pintelon (2002) identified the six categories of losses in TPM: (1) breakdown losses; (2) set-up and adjustment losses; (3) minor stoppage/idling losses; (4) reduced speed losses; (5) defects/rework losses; (6) start-up losses. The first two losses refer to time losses and influence equipment availability. The third and fourth losses denote speed losses and measure the equipment performance efficiency. The last two losses designate the quality of production process and are used to calculate the quality rate of the equipment (Chan, Lau, Ip, Chan, & Kong, 2005). The effectiveness of TPM strategy with regard to these six losses is measured using overall equipment effectiveness (OEE). The measurement of OEE is a function of the availability, performance efficiency, and quality. TPM entails eight main elements/pillars that can be considered as principles/tools of TPM in an organisation.

- Autonomous maintenance
- Performance improvement
- Early equipment management
- Planned maintenance
- Environment health and safety
- Office TPM
- Education and training
- Quality maintenance

The detailed description of these pillars mentioned above is presented in Ahmed, Hassan, and Taha (2005) and Chong, Chin, and Hamzah (2012). The TPM pillars can be collectively used to improve equipment availability and reliability. However, according to Baluch et al. (2012), removing or missing application of any pillars could lead to unattainable results. Likewise, the lack of comprehensive approach for the TPM implementation has resulted in a decrease of 50% TPM initiatives in US. Moreover, there are some deficiencies related to the TPM strategy. TPM concerns the operational issues that handle equipment failures rather than long-term strategic business issues. Levitt (2008) stated that TPM is no longer lean as it focuses primarily on the operational issues of equipment and it would take a long time to implement. Moreover, EPA (2015) highlighted that TPM failed to consider the environmental aspects during equipment efficiency improvement. This leaves potential waste minimisation and pollution prevention opportunities to be more researched.

While referring to major literature on TPM, it was observed that there is a link between TPM and lean as well as LM emerged as an effective maintenance strategy. Levitt (2008) mentioned that TPM and lean are broadly linked. This is clear in some of the literature that considered TPM as a subsection of lean system which mainly focused on enhancing the efficiency and availability of the manufacturing facilities. For instance, Shah and Ward (2003) postulated 21 manufacturing practices as the key features of lean system. They grouped the inter-related and internally consistent practices into bundles. TPM was one bundle which contained four practices: PM, maintenance optimisation, new process equipment, and safety improvement. These four practices sound very generic and not provide practitioners what tools to undertake the maintenance optimisation, or new process equipment. Another study by Mostafa (2011) extended the TPM practices, suggested by Shah and Ward (2003), to include housekeeping, cross-training and teams of maintenance technicians, operator involvement (autonomous maintenance), and information tracking of the work orders. Clearly, these suggested practices indicated another dimension of TPM in lean system by considering human resource perspective. Abdulmalek, Rajgopal, and Needy (2006) gathered 14 lean tools into three areas: quality, production process, and methods. TPM was located under quality area which can be considered as another perspective for TPM in lean environment. It can be concluded that TPM is considered as the foundation for the maintenance process in lean environment which must be supplemented with some lean practices. That is why some studies coined relatively new terms like lean TPM (Georgescu, 2010; McCarthy & Rich, 2004) and LM (Baluch et al., 2012; Okhovat, Ariffin, Nehzati, & Hosseini, 2012; Romano, Murino, Asta, & Costagliola, 2013; Smith & Hawkins, 2004).

LM principles take its lead from lean manufacturing through applying some new techniques to TPM concepts to render a more structured implementation path (Levitt, 2008; McCarthy & Rich, 2004; Romano et al., 2013; Smith & Hawkins, 2004). It is a prerequisite for success as a lean manufacturer that provides a holistic approach to the function of maintenance (Baluch et al., 2012; Soltan & Mostafa, 2014). As lean concept has been taking hold in the manufacturing sector, there is an increasing insight that maintenance must not be seen only from narrow operational perspective dealing with equipment failures and their consequences. Instead, maintenance must be viewed in the long-term strategic perspective and must integrate the different technical and commercial issues in an effective manner. However, LM approach cannot just be a mirror image of a lean manufacturing approach because the business dynamics of asset maintenance and those of production are fundamentally different (Baluch et al., 2012; Brown, Collins, & McCombs, 2006; Clarke, Mulryan, & Liggan, 2010). Therefore, it is clear that there is a need to develop an effective process to collectively integrate lean thinking into the maintenance with long-term strategic perspective. This study addresses such an issue to cover the major deficiencies in the existing literature.

3. Research aim and objectives

This research aims to adopt lean principles and practices/tools and collectively integrate them into the maintenance process. It has adopted recommendations of previous research works such as a study of Davies and Greenough (2010) that emphasised on the necessity of conducting more research in application of lean manufacturing principles in maintenance operations. To achieve the main aim of this research, four main objectives have been established:

(1) To review the LM concept.
(2) To develop a process for adopting lean principles into maintenance processes.
(3) To document the maintenance wastes and establish a scheme of lean practices/tools applied to maintenance.
(4) To develop the HoW that demonstrates the association of lean tools with the maintenance wastes.

4. Research methodology

To achieve the research objectives, this study employed a systematic review of the literature in order to explore major publications related to lean manufacturing and maintenance concepts, especially research works published from 2001 to 2014. Okoli and Schabram (2010) indicate that a systematic literature review is a systematic, explicit, comprehensive, and reproducible method for identifying, evaluating, and synthesising the existing body of completed and recorded work produced by researchers, scholars, and practitioners. According to Denyer and Tranfield (2009), the systematic literature review has become an essential scientific activity.

From the literature review, it has been found that exploration of the applicability of lean principles in maintenance in the existing research works is minimal. Davies and Greenough (2010) and Soltan and Mostafa (2014) state the necessity of conducting more research on applying lean principles in maintenance operations. As an initial step of this research, a seven-step systematic literature is conducted as summarised in Figure 2 to demonstrate development of the proposed LM process. It is noted that these research steps are adapted from several academic sources, such as Joffe (2011), Okoli and Schabram (2010), and Tranfield, Denyer, and Smart (2003).

4.1. Research selection criteria

The research inclusion and exclusion criteria are very critical to the quality assessment of papers (Booth, Papaioannou, & Sutton, 2012). Okoli and Schabram (2010) indicated that simplifying research using these criteria (by reviewing the title and then the abstract when needed) saves the researcher time and effort. In this study, the authors examined research articles by title and then abstracts. In the systematic review of this study, the criteria were addressed in order to clarify the selection of the research-related articles. The following criteria have been considered to include/ exclude the articles:

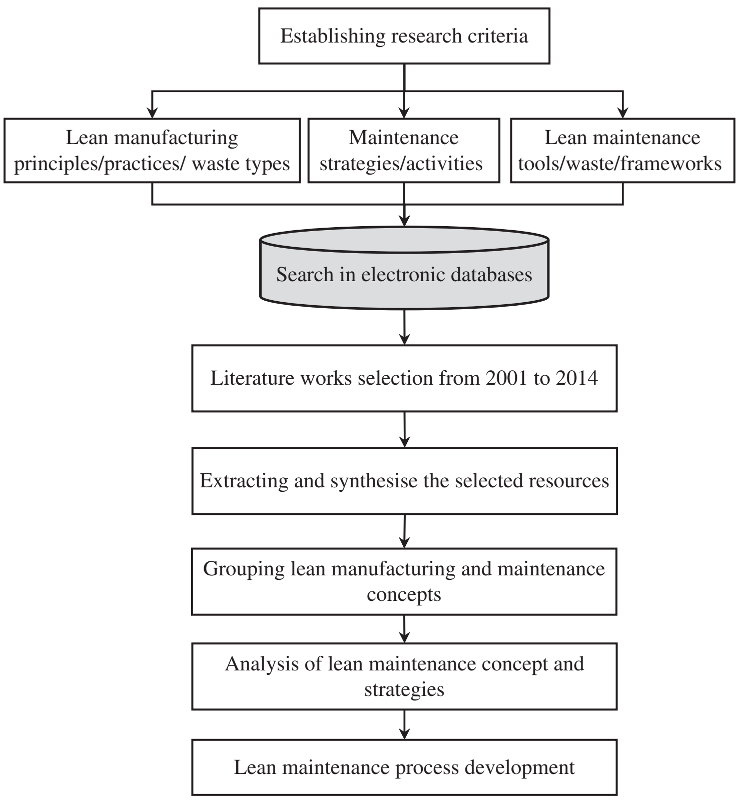

Figure 2. Research methodology framework.

- Articles published between 2001 and 2014 as the rational for considering the year 2001 is that LM as a field of research was firstly addressed by Davies and Greenough (2001)
- Search for articles published in peer-reviewed scientific journals or conference proceedings
- Ensure essential relevance by requiring that selected articles contain at least one of the search keywords in the title or abstract (see Table 1)
- Search well-known online databases which are Taylor & Francis, EBSCO, Emerald, IEEE, Inderscience, ProQuest, Sage, Science Direct, and Springer Link

5. Development of LM in the literature

The screened LM studies are dated from 2001 to 2014 with the total number of 43 retrievable publications as shown in Table 2.

The selection of published LM studies shows that most of the studies were published in the year 2014 and focused on three aspects, namely LM implementation initiative, suggested lean tools, and interrelationship within LM application as illustrated in Figure 3.

From the review of 43 publications, the focus on the LM implementation has been continuously growing since 2011 for general practice and specific industries. The suggested lean tools and interrelationship within the LM initiatives were not in parallel with the LM implementation. The LM tools were found in 18 publications. None of these publications provided a complete set of lean tools. Only two publications in 2012 and 2013 demonstrated the interrelationship within LM application. The low volume of publications indicates that more research in LM is crucially needed, especially in establishing a logical interrelationship between LM concepts and implementation and a complete set of LM tools.

5.1. Lean maintenance

LM term was coined in the last decade of the twentieth century. Smith (2004) defines LM as a proactive maintenance operation employing planned and scheduled maintenance activities through TPM practices using maintenance strategies developed through application of reliability-centred maintenance (RCM) decision logic and practiced by

Table 1. Research primary and secondary keywords.

Time period considered	Search engines used	Primary keywords	Secondary keywords
2001–2014	Taylor & Francis, EBSCO, Emerald, IEEE, Inderscience, ProQuest, Sage, Science Direct, and Springer Link	• Lean maintenance • Lean TPM	• Lean principles AND maintenance • Lean practices AND maintenance • Lean tools AND TPM

Table 2. Review of existing literature on lean maintenance.

S. no.	Author(s) and year	Key aspects covered	Application industry	Suggested lean maintenance implementation	Limitations
1	Davies and Greenough (2001)	(1) Investigate the level of presence of lean thinking within the maintenance domain and its influence and interaction with the maintenance function		No	No
2	Davies and Greenough (2003)	(1) A set of performance measures that can be used to analyse the impact of lean thinking within the maintenance function		No	No
3	Davies (2003)	(1) Explained the contribution of lean thinking to the maintenance of manufacturing system (2) An overall measure of maintenance performance comprised a number of indicators that signify change through maintenance activity has been suggested		No	No
4	Heisler (2003)	(1) Highlight the role of effective planning and scheduling of maintenance process in lean environment	General-planning and scheduling	Lean maintenance process flow	• Present the flow of maintenance processes for the lean maintenance planning and scheduling • No lean tools or principles demonstrated
5	Smith (2004)	(1) Defined the lean maintenance (2) Discussed the elements for lean maintenance success		No	

(*Continued*)

Table 2. (*Continued*).

S. no.	Author(s) and year	Key aspects covered	Application industry	Suggested lean maintenance implementation	Limitations
6	Smith and Hawkins (2004)	(1) Reviewed the history and evolution of lean (2) Explained the lean maintenance element and TPM (3) Discussed the pre-planning and mobilising lean maintenance (4) Introduced the key elements for sustain lean	General	The maintenance management pyramid	• Limited tools provided • Flow of the implementation process is limited
7	Verma and Ghadmode (2004)	(1) A model for ship fleet repair and maintenance based upon lean principles and current best practices	Ship fleet repair	Proposed implementation model for ship fleet repair	• The model contained 7 steps with no interrelationship or logic to apply them • No feedback or measuring of the performance • No lean tools suggested
8	Zwas (2006)	(1) Investigated how lean techniques can be employed in bus and rail maintenance		No	
9	Colbert (2008)	(1) Benefits of integrating lean into IR predictive maintenance programmes (2) Lean concepts/tools are able to better manage and maintain the real value of their IR programmes while drastically increasing their ROI		No	No
10	Van den Heuvel (2008)	(1) Increasing the efficiency of the activities during regular maintenance shutdowns at steel Sheet Plant using lean and six sigma approaches		No	No

11	Marks (2008)	(1) Created an accurate and enhanced CMMS database and a safe and efficient Rotable Plant storage system (2) Explored and implemented an Effective Rotable Plant Management Programme that fulfils the lean maintenance strategy (3) Demonstrated how all value adding in terms of Effective Rotable Plant Management is maintained using very little resources		No	No
12	Yile, Hang, and Lei (2008)	(1) Based on the value stream analysis (VSA), inherit 'value' relation of TBM, RCM, and remanufacture engineering is established (2) A simple layered technology framework of lean maintenance	Frictional clutch maintenance	Maintenance management pyramid	• The pyramid defined the lean maintenance as an integration of 13 practices • No limitation process flow were provided • The lean principles were not included
13	Georgescu and Militaru (2009)	(1) A lean TPM approach to the current understanding of the TPM system (2) 7Ss as a critical first step in any improvement programme; instant maintenance; improvement set-up operations		No	No
14	Thiruvengadam (2009)	(1) A method for assessing the breakdown maintenance factors using a value stream maintenance map in a clearly and precisely measurable technique		No	No

(*Continued*)

Table 2. (*Continued*).

S. no.	Author(s) and year	Key aspects covered	Application industry	Suggested lean maintenance implementation	Limitations
15	Clarke et al. (2010)	(1) One of the most important aspects of lean maintenance is developing an understanding of the maintenance processes and applying a risk-based approach in a pharmaceutical asset maintenance. This involves evaluating whether each element of maintenance practice used adds value to the product and benefits the customer		No	No
16	Davies and Greenough (2010)	(1) A lean practice template which represent activities possible within a company's maintenance department (2) Performance indicators to identify the impact of lean thinking within maintenance activities		No	No
17	Georgescu (2010)	(1) A new maintenance system called lean TPM. It is a systematic approach based on three techniques: the 7Ss as a critical first step in any improvement programme; instantaneous maintenance; improvement set-up operations		No	No
18	Ghayebloo and Shahanaghi (2010)	(1) A MODM model to determine minimum level of maintenance requirements and to satisfy expected reliability level		No	No
19	Sheng and Tofoya (2010)	(1) Four core lean rules (activities, connections, flows, and improvements) transferred in the maintenance context		No	No

20	Ayeni, Baines, Lightfoot, and Ball (2011)	(1) Application of lean within MRO in the aviation industry		No	No
21	Kolanjiappan and Maran (2011)	(1) Application of root cause failure analysis (RCFA), RCM, Failure mode and effect analysis, and maintenance procedure effectiveness analysis	Aircraft maintenance	Schematic diagram for servicing time reduction of aircrafts	• The focus of the diagram is to reduce the service time not to implement lean maintenance • process flow is missing • no lean tools provided
22	Qiang, Zhu, and Li (2011)	(1) The characteristics of the military equipment lean maintenance (MELM) and main components for improving the MELM	Military equipment	Components of MELM	• The MELM contains three stages: models of maintenance, components of MELM, and output • No implementation introduced • Lean tools has been suggested
23	Baluch et al. (2012)	(1) Lean maintenance cannot be a mirror of lean production as the business dynamics of asset maintenance and production are fundamentally different (2) TPM and lean initiatives that allowed organisations to focus on improving the efficiency of production processes		No	No
24	De Silva, Ranasinghe, and De Silva (2012)	(1) Improving maintainability of buildings can promote lean maintenance (2) Challenges of lean maintenance in the construction industry		No	No

(*Continued*)

Table 2. (*Continued*).

S. no.	Author(s) and year	Key aspects covered	Application industry	Suggested lean maintenance implementation	Limitations
25	Huang, Bian, and Cai (2012)	(1) Key technical characteristics of lean maintenance (RCA, FMEA, value stream analysis) (2) Realisation of lean maintenance (LM) through updating maintenance concept, highlighting the academic innovation and integration, and enhancing the culture construction of LM theory (3) A theoretical basis for the equipment maintenance reform	Military equipment maintenance	LM technical supporting frame	• The frame showed the key techniques of LM • Some lean tools have been provided • No implementation of the LM introduced
26	Okhovat et al. (2012)	(1) Developed a strategic framework to provide guidance and support to reach world-class standards both in maintenance and manufacturing processes through continual improvement (2) The framework integrated three process improvement strategies: six sigma, TPM, and lean	General-world-class manufacturing	Framework for world-class standard	• General frame for production and maintenance included TPM, lean, and 6σ • Limited lean tools documented for maintenance process
27	Rastegari (2012)	(1) A maintenance strategy in manufacturing organisation that can be linked to the company's business strategy in lean environment		No	No
28	Tinashe George Tendayi and Fourie (2012)	(1) A framework for implementing a lean in a rolling stock maintenance environment that seeks to eliminate waste, add value, and continuously improve its supply chain	Rolling stock maintenance	Lean maintenance supply chain framework	• Frame for specific case study supply chain • Not incorporated the lean principles • Lean tools are not included

29	Hou, Zhao, Meng, and Ma (2013)	(1) Lean Maintenance System Model for China's hydropower equipment maintenance enterprises by the (2) Application of the lean production theory and ideas, and the model consists of lean culture building, system file structure, maintenance project management, maintenance on-site management and safety management		No	No
30	Jahanbakhsh, Moghaddam, and Samaie (2013)	(1) Benefits of using lean approach in Teen Dairy Industry to reduce the amount of losses and rework of maintenance systems		No	No
31	Romano et al. (2013)	(1) A LRCDA method to reduce scraps and work-in-process in manufacturing context (2) LRCDA merges steps of RCFA, lean maintenance, and TPM	Power cables factory	LRCDA model	• The model is based on the RCDA not lean principles • The model contained limited lean practice within the model
32	Tendayi (2013)	(1) A framework, based on lean thinking tools and relevant performance measures to prove the applicability or otherwise, of lean thinking in an operational maintenance environment outside the traditional domain of manufacturing	Rolling stock maintenance	Framework for lean thinking in maintenance	• Insufficient implementation process flow • Limited lean tools introduced
33	Djurovic and Bulatovic (2014)	(1) Implementation of the 'S5' LEAN methods concept in maintenance, storage, as well as other elements of the business system		No	No
34	Bulatovic and Djurovic (2014)	(1) Lean production cannot be implemented without the use of lean strategy in the equipment maintenance		No	No

(*Continued*)

Table 2. (*Continued*).

S. no.	Author(s) and year	Key aspects covered	Application industry	Suggested lean maintenance implementation	Limitations
		(2) 5S is one of the most basic tools in the lean maintenance			
35	Dunn (2014)	(1) Focus on key elements within each of the work management framework processes that will produce improvements in maintenance productivity and remove waste (1) Three ways in which continuous improvement approaches can further improve Maintenance Productivity and eliminate waste: • Improving maintenance efficiency • Improving the predictive maintenance programme • Eliminating defects		No	No
36	Irajpour, Fallahian-Najafabadi, Mahbod, and Karimi (2014)	(1) Identify and evaluate the effectiveness of a given maintenance strategy and to rank components of maintenance system (2) Using DEMATEL method on maintenance strategy as a guideline to rank the lean components in maintenance	General-rank component of maintenance	Model of effective maintenance strategy	• The model is used to rank the effective elements of maintenance strategy • Lack of model elements dependency • Limited lean tools provided • Lean principles is not incorporated in the model
37	Jasiulewicz-Kaczmarek (2013)	(1) The common elements of the lean and green paradigms introduced for better understanding of synergy between them and overall improvement of maintenance efficiency	General-production management	Lean & green maintenance results	• The frame demonstrated the requirements and results of using lean and green in maintenance process • No presentation of how to incorporate either lean or green in the maintenance

38	Nima, Hesamodin, and Alireza (2014)	(1) Development of a practical model to define an optimised effective maintenance strategy using lean approach		No	No
39	Önder (2014)	(1) How maintenance may contribute to decreasing the environmental impact of production	General-lean green maintenance concept	Reducing environmental impacts and improving efficiency with lean green maintenance	• Generic framework contained four phases: plan, learn, action, and improve • Not comprehensive nor designed based on lean principles • Very limited lean tools were suggested
40	Shou, Wang, Wang, Hou, and Truijens (2014)	(1) Apply BIM and lean concepts to practical maintenance to improve efficiency		No	No
41	Soltan and Mostafa (2014)	(1) Lean and agile can manage the maintenance processes (2) Lean and agile maintenance should be considered as a prerequisite for any successful lean or agile application (3) A framework to measure the performance of maintenance strategies based on lean and agile factors	General	Lean and agile factors in maintenance operations	• No lean tools provided • No implementation process flow provided

(*Continued*)

Table 2. (*Continued*).

S. no.	Author(s) and year	Key aspects covered	Application industry	Suggested lean maintenance implementation	Limitations
42	Stuchly and Jasiulewicz-Kaczmarek (2014)	(1) The maintenance aim has been shifted from production paradigm to sustainable development that resulted in a change towards the product life cycle as well as taking into account economic, environmental, and social aspects (2) Maintenance offers numerous opportunities of decreasing influence of business processes on natural environment and more efficient resources utilisation		No	No
43	Sunjka and Murphy (2014)	(1) Determine the status of lean implementation within South African aircraft maintenance organisations (AMOs)		No	No

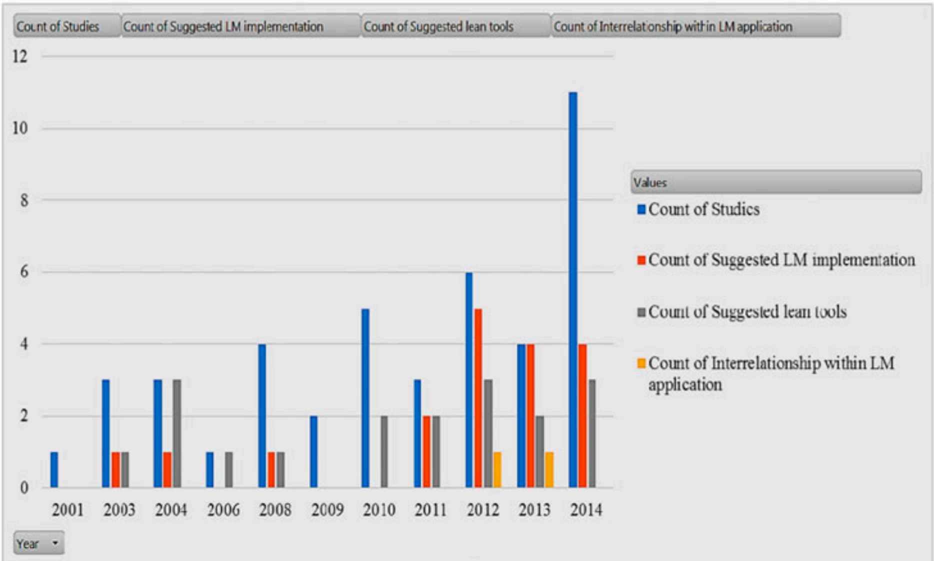

Figure 3. Distribution of lean maintenance studies.

empowered (self-directed) action teams. LM generates a desirable outcome by minimising consumption of inputs (Smith & Hawkins, 2004). LM represents adopting lean principles into the maintenance, repair, and overhaul (MRO) operations. It could reduce unscheduled DT through optimising maintenance support activities and maintenance overhead. The lean tools are representing the lean principles for the implementation process (Mostafa, Dumrak, & Soltan, 2013). To achieve LM improvement effectively, key lean tools such as VSM, 5S, and visual management need to be employed (Smith, 2004; Smith & Hawkins, 2004). A comprehensive lean tools developed for maintenance activities within an organisation include 5S, TPM, OEE, Kaizen, Poka-Yoke, process activity mapping, Kanban, computer managed maintenance system (CMMS), enterprise asset management (EAM) system, and Takt time (Davies & Greenough, 2010; Smith, 2004).

Despite the benefits of LM mentioned earlier, the review of previous studies conducted in this study found that the investigation on the applicability of lean principles into maintenance is marginal. The existing research works have been largely limited to the manufacturing environment where LM is practised as a prerequisite for lean manufacturing (Tendayi, 2013). This proposition has been mentioned in Davies and Greenough (2010) emphasising on the necessity of conducting more research on practical application of lean manufacturing principles in maintenance operations. It was discovered that the previous studies mainly focused on ranking the maintenance strategies based on some specific scope. Moreover, few initiatives have included comprehensive frameworks or models that can integrate lean thinking in operational maintenance environments outside of the manufacturing context. Ghayebloo and Shahanaghi (2010) formulate a model for determining the minimal level of maintenance requirements and satisfying reliability level through the use of the lean concept. Tendayi and Fourie (2013) use a combined approach between QFD and AHP to evaluate the importance of maintenance excellence criteria and prioritise the lean tools upon these criteria. The recent study of Soltan and Mostafa (2014) introduces a framework for measuring maintenance strategies based on lean and agile components, i.e. waste removal and responsiveness. However, the study cannot provide sufficient practical application of lean concept in the maintenance process. Romano et al. (2013) formulate lean root cause and defect analysis (LRCDA) to reduce scraps and work-in-process in manufacturing system. Nevertheless, the LRCDA model introduced is based on RCDA (not lean principles) as well as contains limited lean practice within the model. The paucity of practical application in the existing LM studies provides an opportunity for this study to expand the prevailing knowledge into a new framework for lean integration in the maintenance process.

5.2 Lean tools for maintenance activities

Reducing the NVA within maintenance activities can be accomplished through implementing lean tools (Jasiulewicz-Kaczmarek, 2013). The lean tools that suit the maintenance activities have been stated in previous studies. Smith and Hawkins (2004) identify the key lean tools including VSM, 5S, and visual management. Davies and Greenough (2010) develop a comprehensive lean tools template that represents possible lean activities within the maintenance process within an organisation. The tools are 5S, TPM, OEE, standards, mapping, inventory management, and visual management. Okhovat et al. (2012) suggest six lean tools that fit the maintenance processes of an organisation. These tools include visual control, 5S, seven wastes, single minute exchange of die (SMED), and Poka-Yoke (mistake proofing). Clarke et al. (2010) target eight LM practices as a preparation for delivering lean project objectives in a pharmaceutical organisation. A list of the references including LM tools is demonstrated in Table 3.

6. A proposed LM process

This section demonstrates an attempt to propose a process for adopting lean thinking into the maintenance activities. The process adopts the hypothesis of Womack and Jones (2003) that lean principles can be deployed to all organisations and sectors. Lean principles have being increasingly extended for industrial and service sectors. This is known as lean thinking which refers to the thinking process of lean (Holweg, 2007). The process proposed in this study is designed on the basis of the five lean manufacturing principles stated by Womack and Jones (2003). Some authors including Karim and Arif-Uz-Zaman (2013) develop lean implementation methodology based on the five lean principles for a manufacturing environment. Mostafa et al. (2013) state that lean practices/tools represent lean principles in the implementation process.

The process introduced in this study could be considered as an attempt to pave the way of applying or adopting lean principles to maintenance activities (Figure 4). The process provides guidance and support towards maintenance excellence for an organisation pursuing to extend lean practice to its maintenance department or other organisations starting introducing lean thinking to maintenance department. The process was developed through conceptual integration of five lean principles as they are the backbones of any lean initiatives (Womack & Jones, 2003). The principles specify the value, identify the value stream, flow the value, pull the value, and pursuing perfection. In addition, analysing and addressing limitations of the existing initiatives assist in developing the comprehensive LM process proposed in this study. The process is more flexible and can be adjusted according to any maintenance strategy. It could work

Table 3. Lean maintenance practices/tools reported in previous studies.

	Previous study																	
Lean maintenance tool	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
TPM	*	*	*	*		*	*			*	*			*		*	*	
5S/CANDO	*	*	*	*	*		*		*		*		*	*	*	*		
Kaizen (continuous improvement)	*	*	*	*						*		*		*	*	*	*	*
CMMS/EAM	*					*	*				*			*			*	
Distributed MRO storerooms	*	*				*								*				
RCFA/FMEA	*		*	*		*		*			*						*	
PdM	*	*				*								*			*	
Autonomous maintenance		*					*			*				*			*	
SMED		*			*		*		*									
Poka-Yoke			*	*	*				*	*	*	*	*		*	*		
PDCA										*	*					*		
OEE				*														
Kanban				*				*					*		*	*	*	
Jidoka													*					*
JIT/inventory management			*	*			*						*		*	*		*
RCM						*	*	*			*			*			*	
Process mapping (VSM)				*						*			*			*		
Maintenance and reliability group				*										*				
Work standardisation	*		*	*				*				*		*	*	*		
Story boarding			*	*														
Visual control			*	*	*				*						*			
Work order system			*											*			*	
Self-audit				*														
Supplier association				*														
Open book management		*		*														
Empowered maintenance team												*		*				
Multi-skilled work team												*						
Maintenance crew training and learning							*					*						
Hoshin planning										*							*	*
A3										*								

Note: 1 – Baluch et al. (2012); 2 – Clarke et al. (2010); 3 – Davies and Greenough (2003); 4 – Davies and Greenough (2010); 5 – Djurovic and Bulatovic (2014); 6 – Huang et al. (2012); 7 – Irajpour et al. (2014); 8 – Kolanjiappan and Maran (2011); 9 – Okhovat et al. (2012); 10 – Önder (2014); 11 – Qiang et al. (2011); 12 – Romano et al. (2013); 13 – Smith and Hawkins (2004); 14 – Smith (2004); 15 – Tendayi (2013); 16 – Verma and Ghadmode (2004); 17 – Yile et al. (2008); 18 – Zwas (2006).
*Presence of the lean maintenance practice within the study.

simultaneously and complementary with previous framework developed for shop floor area as it is inclusive for the maintenance processes. The proposed process entails five stages and detailed steps within each stage.

6.1. Stage one: specify the value

The first stage focuses on defining an organisational maintenance system including activities, maintenance planning, strategies, and maintenance crew. In this stage, the employees training on LM wastes are assigned. Furthermore, identifying the types of wastes in maintenance processes is included. The core concept of lean manufacturing is eliminating the seven cardinal forms of waste. The seven cardinal types of waste in the maintenance process can be discussed in the same manner as in the eight waste types identified in the production system (Baluch et al., 2012; Clarke et al., 2010; Davies & Greenough, 2010).

(1) Too much maintenance: performing PM and predictive maintenance (PdM) tasks at intervals more often than optimal which results in the overproduction of maintenance work.
(2) Waiting for maintenance resources: production department is waiting for maintenance personnel to perform the maintenance service. It involves waiting for tools, parts documentation, and buys extra tools and stores them near the job location.
(3) Centralised maintenance: the centralisation of the MRO stores that are far from the job, commonly used repetitive parts that have not been kitted, documentation that must be hunted down, and work orders for machines that are not available all cause excess transportation. Therefore, maintenance personnel spend more time in motion and transportation which do not add value to the process.
(4) Non-standard maintenance: maintenance operations are normally conducted to achieve operation as soon as possible with no standard guidelines. This sometimes eliminates an opportunity to perform a higher quality repair.
(5) Excessive stock: the MRO inventory contains needed materials and spares. Additionally, work-in-process inventories may be used to ensure availability of required materials. Inventory for a maintenance operation also includes the work order backlog. Excessive maintenance work inventory results in slow response, unexpected breakdowns, and a high reactive labour percentage.
(6) Double handling: the wasted motion is usually concentrated around PM tasks. Doing inspection monthly on a pump that has not changed status in three years should be extended longer to quarterly, semi-annually, or annually depending upon the criticality of that piece of equipment.
(7) Poor maintenance: performing incorrect repair is a source of poor maintenance. Incorrect maintenance requires several repeated times to complete the repair job correctly. This affects the maintenance cost and the quality of the product. Applying proper training and detailed procedures can assist in poor maintenance elimination.
(8) Under-utilisation of maintenance crew: maintenance technicians do NVA work or do not perform as required/at the best interest of the organisation.

6.2. Stage two: identify the value stream

This stage includes all maintenance-related activities and processes. The stage starts by mapping the maintenance value stream then locating the wastes sources. This stage ends with setting equipment performance measures such as availability, OEE, and meantime between failures. VSM is used for visualising the flows of information and materials within a supply chain. VSM primarily helps an organisational management to recognise different forms of waste and its sources. One key metric of VSM is value added (VA) time percentage which measures VA activities against NVA activities (Monden, 1998). Standard icons for drawing the current and future VSM are available in Sullivan, McDonald, and Van Aken (2002). These icons should be modified to fit the maintenance activities. In this study, a new set of VSM icons fitting all the maintenance activities was introduced (see Figure 5). The new icons were designed using Edraw Max™

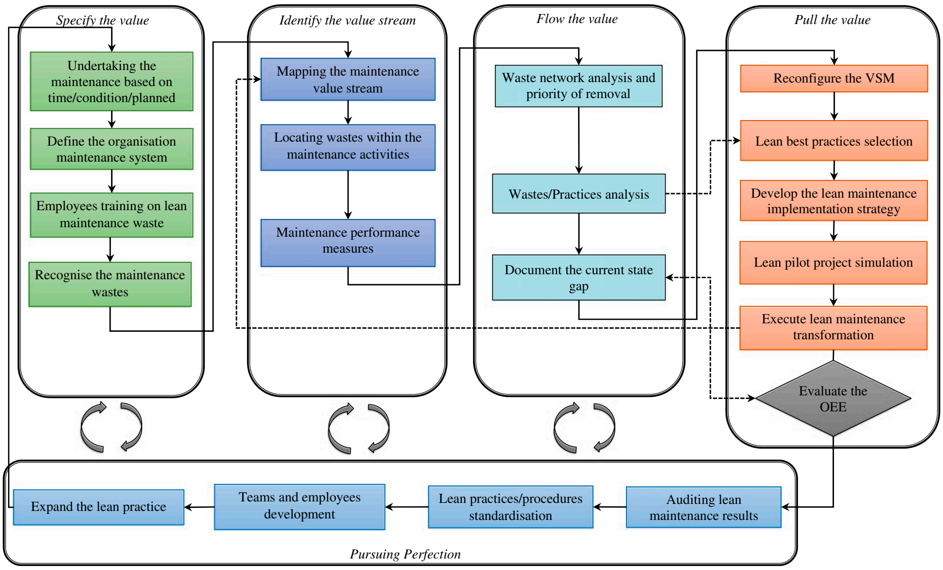

Figure 4. Proposed lean maintenance process.

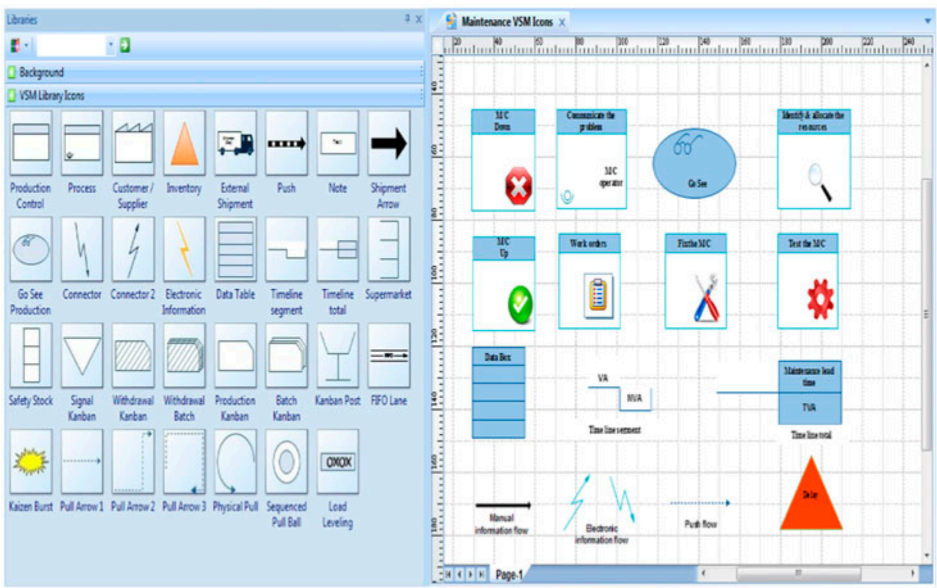

Figure 5. VSM symbols for maintenance activities (developed from Edraw Max software).

professional software package. The discussion of each activity is displayed in Table 4. An example of mapping the maintenance process using these icons for visualising a general current state is displayed in Figure 6.

Table 4. Maintenance VSM symbol description.

	Symbol	Description
(1)	Machine down	Machine need maintenance (e.g. break down, time-based, or condition-based)
(2)	Communicate the problem	Machine operator communicates the maintenance department
(3)	Go see	Maintenance personnel go and check the machine condition and report to the maintenance department
(4)	Identify and allocate resources	Identification and locating of appropriate resources such as tools, spare parts, manpower for fixing an equipment
(5)	Work orders	Generating maintenance work order through the maintenance software
(6)	Machine fix	Steps for fixing the machine
(7)	Test the machine	Testing of machine after repair until first good part is produced
(8)	Delay	Waiting time due to unavailability of resources (e.g. technician, tools, and spare parts)
(9)	Manual information flow	The flow of information from reports
(10)	Electronic information flow	The flow of information from the internet, intranet, local area network, wide area network, and other notes
(11)	Push flow	Represent the physical flow sequence of the maintenance activities
(12)	Time line segment	Represent the VA and NVA time for each activity
(13)	Time line total	Represent the maintenance lead time (down time)
(14)	Data box	Record the information of each maintenance process including cycle time (C/T), changeover time (C/O), and number of employees

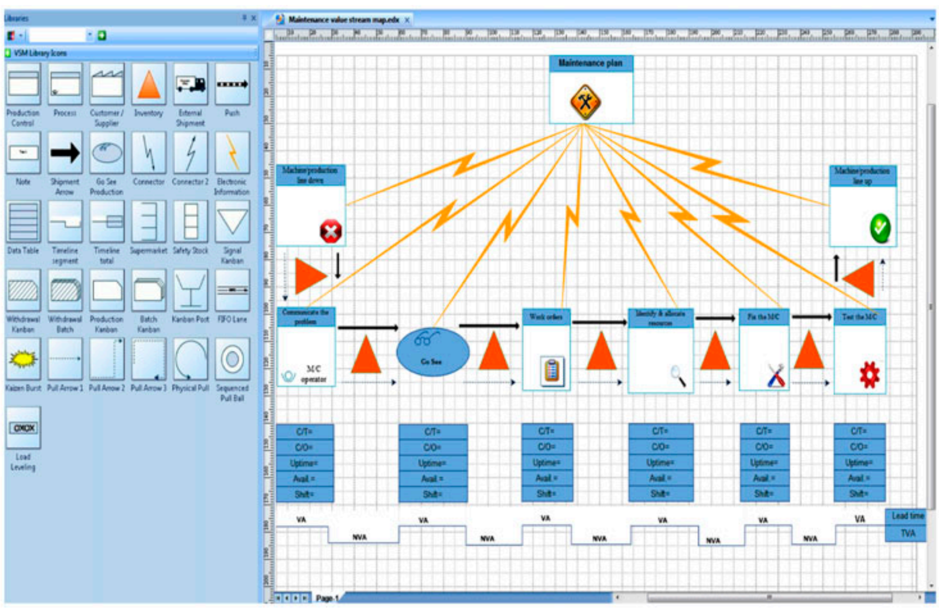

Figure 6. Example of general maintenance state map (developed from Edraw Max software).

6.3. *Stage three: flow the value*

The process of ‘flowing the value’ starts from waste network and waste/practices analyses before the results of the analyses are documented at the current state gap of maintenance using the calculation of OEE within an organisation. The documentation of lean practices for maintenance was conducted through the literature presented in Table 3 through marking out the most frequently suggested practices in these studies and then constructed the hierarchical scheme for LM practices as demonstrated in Figure 7. The structure is similar to Shah and Ward (2003), however, for the use of this structure is dedicated to the maintenance process not the manufacturing process. The structure consists of two levels and four bundles: just-in-time (JIT), total quality management (TQM), human resource management (HRM), and TPM and practices assigned under each bundle. The scheme can be used to indicate the association between the eight types of maintenance waste and the LM practices. The success of the LM depends on the application of each bundle. Each practice provides some benefits within the maintenance process. As a result, the performance of a whole maintenance department can be improved. The four LM bundles are briefly explained below.

6.3.1. JIT bundle

The JIT bundle encompasses all practices which are designed to reducing and eliminating unnecessary inventory and waiting in maintenance activities. These practices are Kanban, SMED, work standardisation, Takt Time, visual control, distributed MRO storeroom, and CMMS.

6.3.2. TQM bundle

The TQM bundle aims at continuously improving and sustaining the quality of products and processes through the participation of management, workforce, suppliers, and

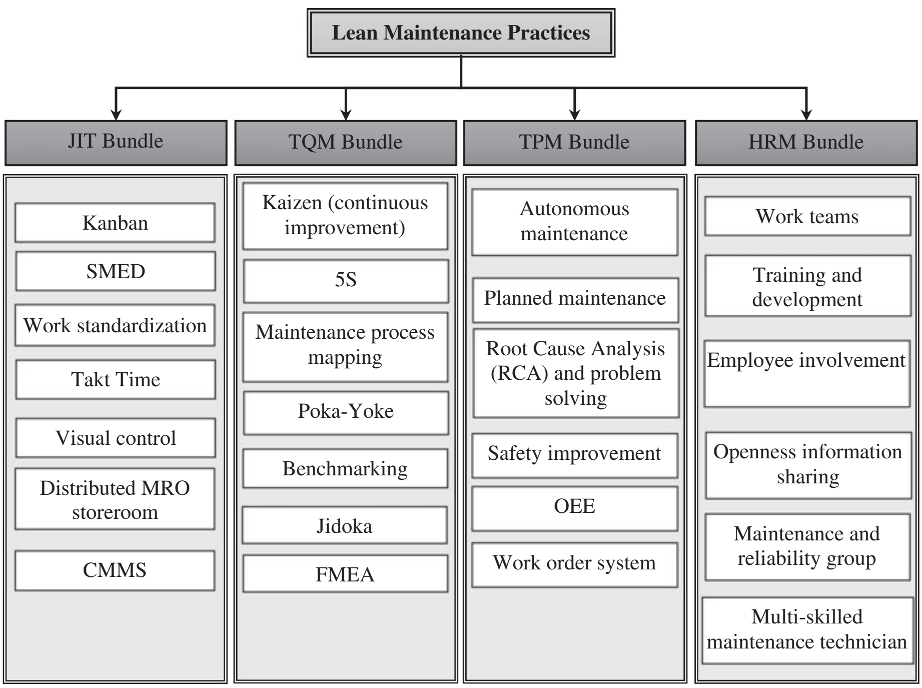

Figure 7. Scheme for lean maintenance practices.

customers, in order to meet or exceed customer expectations (Cua et al., 2001). The practices of TQM are customer focus, leadership, strategic quality planning, use of information and analysis, management of people (participation and partnership), and continuous improvement (Chin, Rao Tummala, & Chan, 2002). This ensures higher customer satisfaction, better quality of products, and higher market share; improving the competitiveness, effectiveness, and flexibility of the whole organisation (Pheng & Chuan, 2001). In this study, the TQM bundle consists of Kaizen, 5S, maintenance process mapping, Poka-Yoke, benchmarking, Jidoka, and FMFA.

6.3.3. TPM bundle

The TPM bundle incorporates all practices that are designed to maximise the equipment effectiveness. The bundle contains autonomous maintenance, planned maintenance, root cause analysis (RCA) and problem solving, safety improvement, OEE, and work order system. The concept of TPM was developed in Japan by Seichii Nakajima aiming at achieving zero losses (e.g. zero breakdowns, zero defects, zero accidents) and attaining the Takt time through improving and maintaining equipment to its highest performance level (Brown et al., 2006). TPM can be integrated with lean in order to distinguishing and attacking six big losses which are reducing the effectiveness of equipment (Rodrigues & Hatakeyama, 2006). These six categories of losses are (1) breakdown losses, (2) set-up losses, (3) minor stoppage/idle losses, (4) reduced speed losses (equipment speed is slow than the designed speed), (5) rework losses, and (6) start-up losses (start-up after periodic repair, start-up after holidays, start-up after lunch breaks, and start-up after suspension) (Waeyenbergh & Pintelon, 2002).

6.3.4. HRM bundle

The HRM bundle encompasses all the practices to ensure that the human resources of an organisation are used in such a way that the employer obtains the greatest possible benefit from their abilities. At the same time, the employees obtain both material and psychological rewards from their work (Hiltrop, 1996). The HRM practices form an organisation performance through increase employees' knowledge, skills, and abilities (KSAs), motivate employees to leverage their KSAs for the firm's benefit and employees empowerment. In addition, work teams, performance appraisal, and information sharing have been recommended to enhance an organisation performance (Huemann, Keegan, & Turner, 2007). In this study, the HRM bundle includes work teams, training and development, employee involvement, openness information sharing, maintenance and reliability group, and multi-skilled maintenance technician.

6.4. Stage four: pulling the value

The fourth stage is to confirm that an equipment (i.e. considered as the customer in the maintenance process) is pulling the value through all maintenance processes. The execution of lean principles takes place at this stage. The stage involves steps in reconfiguring the VSM or designing the future stream map, selecting LM practices, developing the lean transformation strategy, and evaluating the OEE.

6.4.1. Association between maintenance wastes and LM practices

Selecting LM tools is the next step after identifying and discussing the types of waste and lean tools. It assists an organisation to achieve LM targets by associating suitable tools to tackle the spotted waste types. The QFD is suggested in this study to develop the association between these tools and wastes. Mostafa (2011) suggested using QFD to assign the lean practices for each waste. Nonetheless, the study was in a general manufacturing environment rather than a maintenance process. Likewise, Tendayi (2013) applies QFD coupled with AHP to rank the maintenance excellence criteria with some lean tools. The study focused only on a certain case study of rolling stock maintenance. It used limited lean tools and did not include the maintenance wastes. In contrast to Tendayi (2013), this study has identified 26 lean tools for maintenance (see, Figure 7) and eight types of maintenance wastes (discussed in Section 6.1). QFD is a structured tool that identifies important customer expectations and translates them into appropriate technical characteristics which are operational in design, verification, and production. QFD enables resources to be focused on meeting major customer demands. Figure 8 displays the structure of QFD which is frequently called a house of quality (HOQ) because of the shape presented (Bottani & Rizzi, 2006).

The HOQ comprises customer requirements (horizontal axis) and technical characteristics (vertical axis). The customer axis designates what customers require, importance of the requirements, and competitive performance. The customer requirements are often referred as what's. The technical axis describes the technical characteristics that affect customer satisfaction directly for one or more customer expectations. Moreover, on the technical axis are the correlations, importance, and targets of the technical characteristics and technical competitive benchmarking. The technical characteristics are denoted as How's, meaning how to address what's. The technical targets are accordingly called

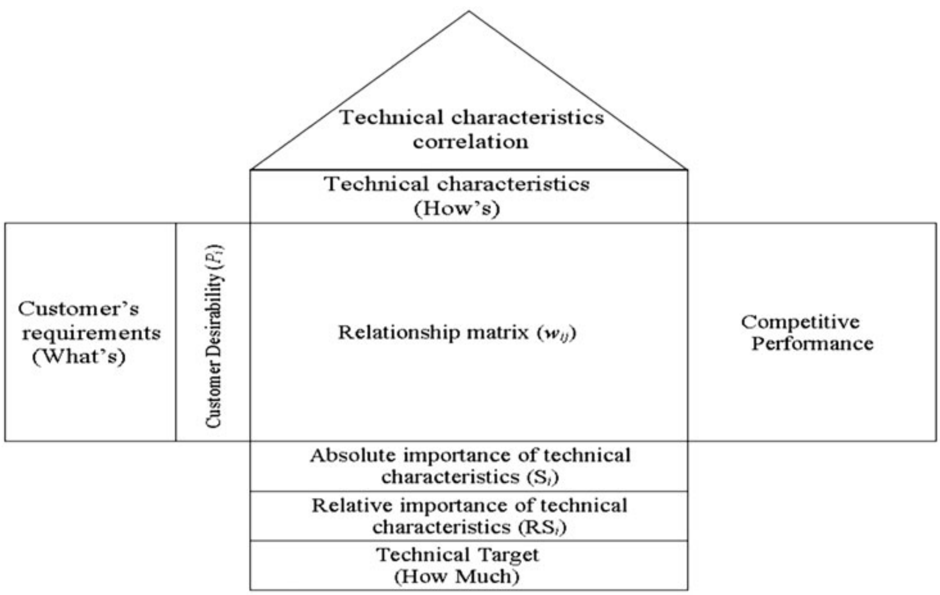

Figure 8. House of quality.

How Much. The interrelationships between customer wants and technical characteristics are evaluated in the relationship matrix.

6.4.2. *House of Waste*

The HoW is developed in this study to demonstrate the maintenance wastes/lean tools association. HoW identifies the importance of each LM tool in the elimination of each waste type as demonstrated in Table 5. It has two main parts: the horizontal part 'What's' which contains information relevant to the waste types and the vertical part 'How's' which comprises corresponding LM tools. The basic process underlying 'How' resides in the centre of the matrix where intersect of maintenance waste types and lean tools provides an opportunity to examine each waste type versus each tool.

Five steps in developing the wastes/tool association using HoW are briefly described as follows:

(1) List the waste types within the maintenance process in the horizontal axis.
(2) Determine each waste priority (*Pi*), which rates the significance of each waste to the maintenance performance. Otherwise, it can be based on the waste occurrence or cost of removal. A scale of 1 to 9 can be used, where 9 is given to extremely important, 7 strongly important, 5 to very important, 3 to important, and 1 to not important.
(3) List LM tools on the vertical axis. An organisation can state suitable LM tools for their own maintenance process in terms of the application cost of LM tools.
(4) Identify the interrelationships between wastes and tools (w_{ij}). The strength of relationship may be classified into three levels, where a rating of 9 is assigned to a strong relation, 3 to a medium relation, and 1 to a weak relation. Each tool must be interrelated to at least one waste; one waste must also be addressed by at least one tool. This ensures that all wastes are concerned in the maintenance removal planning, and all tools are properly established.
(5) Calculate the score (S_j) and (RS_j) to rank each LM tool. The following formula can be used to calculate the score

$$S_j = \sum_{i=1}^{8} w_{ij} P_i, \ \forall j \tag{1}$$

$$RS_j = \frac{S_j}{\sum_{j=1}^{26} S_j}, \ j = 1, \ldots, 26 \tag{2}$$

where

P_i relative priority of ith waste
i type of maintenance waste, $i = 1, 2, \ldots, 8$
T_j LM tool, $j = 1, 2, 3, \ldots, 26$
w_{ij} numerical VA to position (i, j) of the HoW matrix. This refers to the weight of eliminating waste ith by tool jth. Numerical scale can be (9, 3, 1)
S_j score of tool jth over the total types of waste
RS_j relative score of tool jth over the total score of tools

Table 5. House of Waste.

What's (*maintenance wastes*)	Waste priority	How's (*lean maintenance tools*) Kanban	SMED	Work standardisation	Takt Time	Visual control	Distributed MRO storeroom	CMMS	Kaizen	5S	Maintenance VSM	Poke Yoke	Jidoka	Benchmarking	FMEA	Autonomous maintenance	Planned maintenance	RCA	OEE	Work order system	Work teams	Training and development	Employee involvement	Openness information system	Maintenance & reliability group	Multi-skilled technician	Safety improvement
To eliminate too much maintenance	P_1	w_{11}	w_{12}	w_{13}	w_{14}	…																			…	w_{125}	w_{126}
To eliminate waiting for resources	P_2	w_{21}	w_{22}	w_{23}	w_{24}	…																			…	w_{225}	w_{226}
To eliminate centralised maintenance	P_3	w_{31}	w_{32}	w_{33}	w_{34}	…																			…	w_{325}	w_{326}
To eliminate non-standard maintenance	P_4	w_{41}	w_{42}	w_{43}	w_{44}	…																			…	w_{425}	w_{426}
To eliminate excessive stocks	P_5	w_{51}	w_{52}	w_{53}	w_{54}	…																			…	w_{525}	w_{526}
To eliminate double handling	P_6	w_{61}	w_{62}	w_{63}	w_{64}	…																			…	w_{625}	w_{626}
To eliminate incorrect maintenance	P_7	w_{71}	w_{72}	w_{73}	w_{74}	…																			…	w_{725}	w_{726}
To eliminate underutilisation of maintenance crew	P_8	w_{81}	w_{82}	w_{83}	w_{84}	…																			…	w_{825}	w_{826}
LM score		S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9	S_{10}	S_{11}	S_{12}	S_{13}	S_{14}	S_{15}	S_{16}	S_{17}	S_{18}	S_{19}	S_{20}	S_{21}	S_{22}	S_{23}	S_{24}	S_{25}	S_{26}
Relative score		RS_1	RS_2	…																					…	RS_{25}	RS_{26}
Rank																											

The score S_j represents the absolute importance of tool *j*th over all types of wastes. The relative score RS_j refers to the importance of the tool *j*th over all tools. According to Bottani and Rizzi (2006), the technical characteristics are usually ranked based on relative importance rather than absolute importance. Therefore, LM tools should be prioritised based on RS_j. The higher the RS_j, the more important the LM tool that should be incorporated in order to eliminate the waste.

6.5. *Stage five: pursue perfection*

The last stage is to pursue the complete waste elimination from maintenance processes. This could be achieved through auditing the LM results, standardise the lean tools and procedures, teams and employees developments and expand the lean practice.

7. **Implications of proposed LM** process

Most of literature works on lean implementations fall into the manufacturing environment albeit LM is essential part for the lean manufacturing system (Soltan & Mostafa, 2014; Tendayi & Fourie, 2013). Plethora of studies included and mentioned lean and maintenance concepts (see Table 2). Nevertheless, the integration of lean principles into the maintenance environment has not evidently received full attention. The common aspects among the previous studies were (1) introducing partial lean tools to be applied in the maintenance process; (2) developing diagrammatic structures (model, pyramid, or scheme) with unspecified sequence of LM implementation; and (3) lack of proper structure. Consequently, some researchers including Davies and Greenough (2010) and Soltan and Mostafa (2014) have proposed more research on incorporating lean principles in the maintenance activities. Therefore, this study proposed a LM process to cover most of the limitations or deficiencies of the existing suggested LM initiatives.

The proposed LM process is a straight forward, comprehensive, and easy to understand for maintenance practitioners and maintenance strategy decision makers. The benefits of the proposed process can be summarised as:

(1) The process is straightforward and easy to comprehend. This is because of the simple structure that is combined in the process.
(2) A systematic procedure of applying the five lean principles into maintenance activities can result in better understanding from an organisation's management view.
(3) All advantages of lean are kept as the process focus. These advantages are integrated and systemised in the steps of the process.
(4) Application of the process establishes pursuing a perfectionist culture in an organisation. This is done through auditing the LM results, standardisation, team's development, and expansion of the practice. Hence, with every iteration of the process, an organisation maintenance activities move a further step towards maintenance excellence.
(5) Aligning the human resource aspects (maintenance employees training and development) with other steps can bring high potential for a comprehensive and sustainable LM implementation process as well as overall process improvement in an organisation.
(6) The process promotes the teamwork and problem solving cultures to ensure high-quality outcomes of the implementation process.

(7) The maintenance process can be converted to be a predictive and proactive system that provides the reliable process using lean principles. As a result, it enhances the maintenance excellence and world-class manufacturing as maintenance and manufacturing are inseparable (i.e. reliability and availability of manufacturing facilities).
(8) The process can be applied to all manufacturing and non-manufacturing organisations that are pursuing the world-class status in their maintenance function. The process suits those organisations either in pursuing to transfer lean thinking to their maintenance departments or starting lean transformation from the maintenance department.
(9) Hitherto, some initiatives have been developed for specific larger size organisations such as shipbuilding and military (see Table 3). However, the proposed process can be accepted within all level of skills and organisational sizes. This is due to the fact that the process is more flexible and can be adjusted according to any maintenance strategies.
(10) The proposed process is precisely documented and discusses the maintenance wastes and LM tools. It is to enhance the understanding the waste elimination and lead to successful LM implementation.
(11) The process presented wastes/tools association to assign LM tools for each waste type. This leads to an effective waste elimination process and sustainable outcomes.

8. Conclusion

Maintenance is a critical contributor to progressing towards world-class manufacturing of an organisation. It has rapidly grown into a very complex undertaking as technologies, competition, and product characteristics have evolved. In order to achieve world-class performance, the maintenance strategies should be linked to manufacturing strategies such as the lean concept. Applying an effective maintenance strategy can ensure a high degree of utilisation, reliability, and availability of manufacturing facilities especially in a continuous production process. This study has introduced a process to adopt lean into maintenance activities. The process highlights types of NVA maintenance activities, a package of VSM symbols to capture the maintenance activities, LM tools scheme, and tools/wastes association. Moreover, it promotes the culture of continuous improvement aiming at maintenance excellence. In general, any improvements attained from implementing the suggested process might take time to transform maintenance activities into LM. Nevertheless, commitment and direct involvement of an organisational management along with employee training and teamwork development can be a catalyst to accelerate the transformation process. The proposed LM process can be applied in real conditions to test its validity and reliability of the process. This can be considered as a further suggestion to the proposed process in this research. Hence, application of the process in different industrial sectors and a wide range of manufacturing companies can contribute to additional empirical evidence.

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ORCID

Sherif Mostafa http://orcid.org/0000-0002-5708-3770
Jantanee Dumrak http://orcid.org/0000-0002-5752-0707
Nicholas Chileshe http://orcid.org/0000-0002-1981-7518

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