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INVESTIGATING CAUSAL RELATIONSHIP AMONG LEAN MAINTENANCE FACTORS USING FUZZY DEMATEL METHOD

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ABSTRACT

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Associated with the growing industry, challenging circumstances, and competitive environment all around the world; effectiveness and efficiency of maintenance management became much more critical. With the increasing importance of maintenance, various maintenance methodologies have been applied to provide sustainability in production. After the involvement of lean approach, maintenance management focused more on the elimination of wastes and continuous improvement. However, it is very important to know the characteristics and the relationships between lean maintenance factors to perform these activities efficiently. Although some of the previous researches investigated relationship between lean maintenance factors, and presented roadmap for the organizations; none provided sufficient evidences about these influences to guide executives who desire to apply lean maintenance. This study therefore aims to contribute to these gaps in the literature as described below:

1. Presenting cause and effect relations between lean maintenance management factors.
2. Building a strategy map to provide managerial insights to the decision makers in the industry for the implementation of lean maintenance.

In line with this objective, a systematic approach was considered in this study. Fuzzy DEMATEL which is a Multi Criteria Decision Making (MCDM) method was used to conduct the study to create a strategy map considering cause and effect relations of lean maintenance factors, and the analyzes were based on the evaluations of the experts who have various experiences in the industry.

Keywords: Maintenance, Lean Maintenance, MCDM, Fuzzy DEMATEL.

ÖZ

YALIN BAKIM FAKTÖRLERİ ARASINDAKİ NEDENSEL İLİŞKİNİN FUZZY DEMATEL YÖNTEMİ KULLANILARAK ARAŞTIRILMASI

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2020

Tüm dünya üzerinde; gelişen endüstri, zorlayıcı şartlar ve rekabetçi ortam ile birlikte bakım yönetiminin etkinliği ve verimliliği oldukça kritik hale gelmiştir. Bakım faaliyetlerinin artan önemiyle birlikte üretimde sürekliliği sağlamak amacıyla çeşitli bakım yöntemleri uygulanmıştır. Yalın felsefesinin dahil olmasından sonra bakım yönetimi daha çok kayıpları ortadan kaldırmaya ve sürekli iyileştirme faaliyetlerine odaklanmıştır. Ancak bu faaliyetleri etkin bir biçimde gerçekleştirebilmek için yalın bakıma etki eden faktörlerin özelliklerinin ve bu faktörler arasındaki sebep sonuç ilişkilerinin bilinmesi büyük önem taşımaktadır. Geçmişte, yalın bakıma etki eden faktörler arasındaki ilişkiyi inceleyen ve şirketler için yol haritası sunan çalışmalar olmakta birlikte; bu çalışmaların yalın bakım stratejisi uygulamak isteyen yöneticilere yeterli kanıta dayalı bir öneri sunamadığı görülmüştür. Dolayısıyla bu çalışma, literatürdeki aşağıda belirtilen eksikliklere katkı sunmayı amaçlamıştır:

1. Yalın bakım yönetimine etki eden faktörler arasındaki sebep sonuç ilişkilerinin ortaya koyulması.
2. Yöneticiler için yalın bakım uygulaması esnasında yol gösterici ve aydınlatıcı bir stratejik haritanın oluşturulması.

Bu amaç doğrultusunda, bu çalışma içerisinde sistematik bir yaklaşım göz önünde bulundurulmuştur. Yalın bakım faktörlerinin sebep sonuç ilişkilerine dayanan stratejik haritanın oluşturulabilmesi için çok kriterli karar verme (ÇKKV) tekniklerinden biri olan Fuzzy DEMATEL yöntemi kullanılmıştır ve yapılan analizler endüstride çeşitli tecrübeleri bulunan uzman değerlendirmelerine dayandırılmıştır.

Anahtar Kelimeler: Bakım, Yalın Bakım, ÇKKV, Fuzzy DEMATEL.

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Finally, I would like to express special thanks to my wife, Duygu Aydınel for her support throughout the entire process.

Yunus Aydınel

İzmir, 2020

TEXT OF OATH

I declare and honestly confirm that my study, titled "INVESTIGATING CAUSAL RELATIONSHIP AMONG LEAN MAINTENANCE FACTORS USING FUZZY DEMATEL METHOD" and presented as Master's Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Yunus Aydınel

22 April 2020

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1. INTRODUCTION

Along with the increase of mechanization and capital investment on machinery, maintenance took a much more important role in the industry (Düzakın and Demircioğlu, 2005). Today, it is accepted by everyone that maintenance is essential for productivity, quality and safety of operation (Parida et al., 2005).

Despite the general meaning is known by most of the people, there are various definitions of maintenance to have a better understanding. Maintenance Engineering Society of Australia (MESA) shares the definition in Australian Standards which says maintenance is a process of restoring or retaining an equipment to its optimum condition (MESA, 1995). They also support the idea of US Army Material Command (1975), indicates that maintenance consist of repair, servicing, condition determination and all actions necessary for retaining a system or product in a serviceable condition. However, MESA claims that these definitions conflict with their broad view in the study. MESA defines maintenance as achieving required asset capabilities within a business or economic context.

According to the definition of The British Standards Institute (1984), maintenance combines technical and related administrative activities needed to keep or restore machines, installations and assets in good condition. Maintenance also aims to achieve desired output in minimum resource cost without any safety or system condition restrictions (Kelly, 1989). In a similar way, Tsang et al. (1999) claims that engineering decisions and related actions to optimize desired equipment capability are very important for maintenance; and it is also essential to have ability to perform specified function associated with capacity, rate, quality, safety and responsiveness.

In consideration of the definitions of maintenance, objectives of maintenance can be summarized as four main titles according to Dekker (1996). Primary objective of maintenance is to keep desired reliability, availability, efficiency and capability of production systems by ensuring required product quality. Secondly, maintenance needs to ensure asset management to keep system in proper condition. One of the most important objectives of maintenance is ensuring safety of the equipment. Safety has a significant role since failures can cause very big results especially in some specific areas such as airplanes, nuclear or chemical plants; so risk needs to be minimized. As the last one, ensuring human well-being is also an objective whereas maintenance approach needs to be people oriented.

There have been a long journey of maintenance approach and maintenance techniques as shown in Fig.1. Over the years, the importance of maintenance has increased. Correspondingly, employees working in the maintenance area and cost of the maintenance spending have increased (Garg and Deshmukh, 2006). There have been various maintenance strategies throughout history and they have been developed with the same way of the development of manufacturing systems (Shanin et al., 2012). In 1738, industrial revolution started in UK and people testified the invention of steam engine by James Watt in 1765. In those years, maintenance was irrelevant since the items were overdesigned due to lack of proper design knowledge. During the early twentieth century industrial machines were integrated into manufacturing areas and number of skilled employees working in maintenance area increased, but maintenance was in the background in contrast with the production. Production was holding its privilege and maintenance strategy was "Operate to Fail" (Gupta et al., 2017). In other words, maintenance was counted as a necessary evil since there was not any chance to avoid breakdown and cost of the maintenance was inevitable (Parida and Kumar, 2006). Until 1940s, maintenance cost was considered as unavoidable and only maintenance strategy was corrective maintenance (Garg and Deshmukh, 2006). Corrective maintenance was the one mostly used by the manufacturing companies since the expectation from maintenance was repairing broken or failed equipment. Downtime of this maintenance had no privilege, production was the important one. From past to present maintenance became a complex function which includes technical and management skills and keeps its flexibility within the dynamic business circumstances (Mostafa et al., 2015). After 1950s, the first scientific approaches to maintenance revealed. Time-based preventive maintenance programs were began to apply in many companies (Dekker, 1996). After the Second World War, maintenance was started to be considered as an important support in terms of manufacturing. Between 1950 and 1980, perception to the maintenance cost was changed and it was noticed that maintenance can be planned and controlled with the rising of methods such as Preventive Maintenance and Condition Monitoring (Parida and Kumar, 2006). The evolution of Preventive Maintenance was a milestone for maintenance to be considered as a way for profitability after the Second World War (Reason, 1997). From past to present maintenance methodology has evolved with numerous approaches. With the increasing importance of profitability, efficiency and eliminating wastes; Lean Maintenance strategy was born (Gupta et al., 2017). Beside all manufacturing strategies, Lean Maintenance took a very important place in the industry with the involvement of lean culture. Lean is a Japanese concept which aims to eliminate all losses and improve efficiency with the participation of all team members (Mostafa et al., 2015). With the help of lean practices, many companies pursue to increase their profitability in the industry today. Due to the benefits and ease of implementation of Lean Maintenance, the main purpose of this study is to present a roadmap for executives to perform Lean Maintenance successfully.

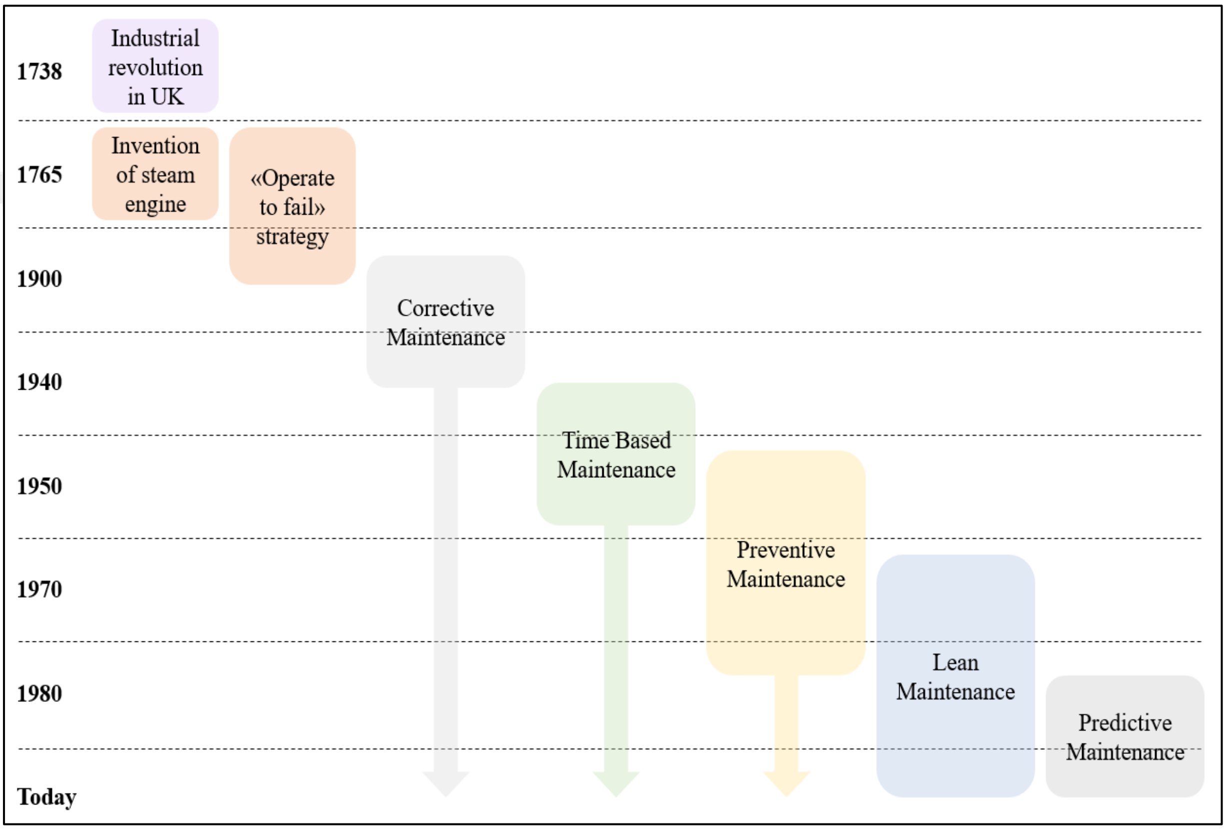

Fig. 1 History of Maintenance Approach

2. MAINTENANCE MANAGEMENT

In the existing literature, maintenance strategies are categorized in interchangeable names and the most common strategies are discussed below.

2.1 Corrective Maintenance

Corrective Maintenance (CM) is also known as Breakdown Maintenance and aims to decrease severity of equipment failures when they reveal. Main focus of CM is to repair an equipment after failure and bring back to production in a short time as far as possible to avoid high loss of production (Sheut and Krajewski, 1994). It is not the most preferred strategy in the industry as of today, however CM should not be ignored since there is always a probability of the failure of a critical process and reformative actions need to be taken. Therefore CM always needs to be considered as a part of maintenance strategy (Finch and Gilbert, 1986). Besides its benefits, CM can be very expensive if the failure causes associated damage to the other equipment in the area (Horner et al., 1997). As stated by Sheut and Krajewski (1994), some of the common manners of CM are machine redundancy, inventory buffers, worker flexibility, and increased service crews.

2.2 Preventive Maintenance

Finch and Gilbert (1986) defines Preventive Maintenance (PM) as periodic observation of equipment and machines to prevent possible failures or breakdowns in advance. Ollila and Malmipuro (1999) also states that the meaning of PM is time scheduled maintenance routines and main task of PM is to evaluate equipment condition and take necessary actions for avoiding production stoppages. This maintenance approach is also known as Time Based Maintenance (TBM) or Periodic Maintenance. Some of the advantages of Preventive Time Based Maintenance are; maintenance cost can be decreased by identifying the items with high maintenance costs and replacing or repairing them prior to failure, service charges are predictable and inventory is reduced, decrease on the number of large scale repairs (Wyder, 1977).

2.3 Condition Based (Predictive) Maintenance

Condition Based Maintenance (CBM) is a predictive approach and purposes to make decisions about replacement or repair about existing or future condition of the equipment. Components of CBM are signal processing techniques and sensors which allows condition monitoring (Raheja et al., 2006). Main benefits of CBM are to increase availability, reliability and life cycle costs of the equipment by assigning necessary actions with the help of data collection through condition monitoring (Golmakani and Fattahipour, 2011). Techniques such as monitoring vibration, ultrasonic testing, thermal imaging, and oil analysis are used for CBM and monitored parameters direct the crew about the correct time to perform required maintenance activities to avoid failure (Al-Najjar and Alsyouf, 2003). Some of the applications using CBM techniques are shown in Table 1.

Table 1 Applications of CBM Techniques (adapted by Liggan and Lyons, 2011)

Technique	Applications		
Monitoring Vibration	Rotating equipment	Motors	Fan balancing
Ultrasonic Testing	Electrical arcing	Valve integrity	Leak detection
Thermal Imaging	Mechanical overheat	Insulation	Electrical overheat
Oil Analysis	Equipment overheat	Wear and tear	Oil degradation

2.4 Reliability Centered Maintenance

Reliability Centered Maintenance (RCM) is a strategy which focuses on reliability critical equipment and parts (Dekker, 1996). Data collection and historical failure analysis are essential for RCM implementation to be able to determine existing condition of the equipment (Vishnu and Regikumar, 2016). It is more important for RCM approach to understand results of a failure rather than the technical characteristics of the failure itself. Accordingly RCM is one of the most preferred strategy to retain operational efficiency in critical industries such as aircraft, aerospace, nuclear, railway networks, gas and oil, power industry, ship maintenance, chemical industry (Khamis et al., 2000; Carretero et al., 2000).

2.5 Total Productive Maintenance

Total Productive Maintenance (TPM) is a maintenance strategy that aims to sustain high equipment effectiveness through collaboration of the entire organization (Rajput and Jayaswal, 2012). Main characteristic of TPM is the involvement of employees from each level in the organizations. Operators also have a voice in the system. Some of the other important benefits of TPM are to increase productivity and

Overall Equipment Efficiency (OEE), decrease customer complaints, decrease manufacturing cost, deliver customer needs on time, and build sense of ownership on the workers (Vankatesh, 2007). As Japan Institute of Plant Maintenance proposed, Ahuja and Khamba (2008), Ranteshwar et al. (2012), and Pomorski (2004) mentioned that there are eight basic pillars or elements of TPM initiatives as shown in Fig. 2.

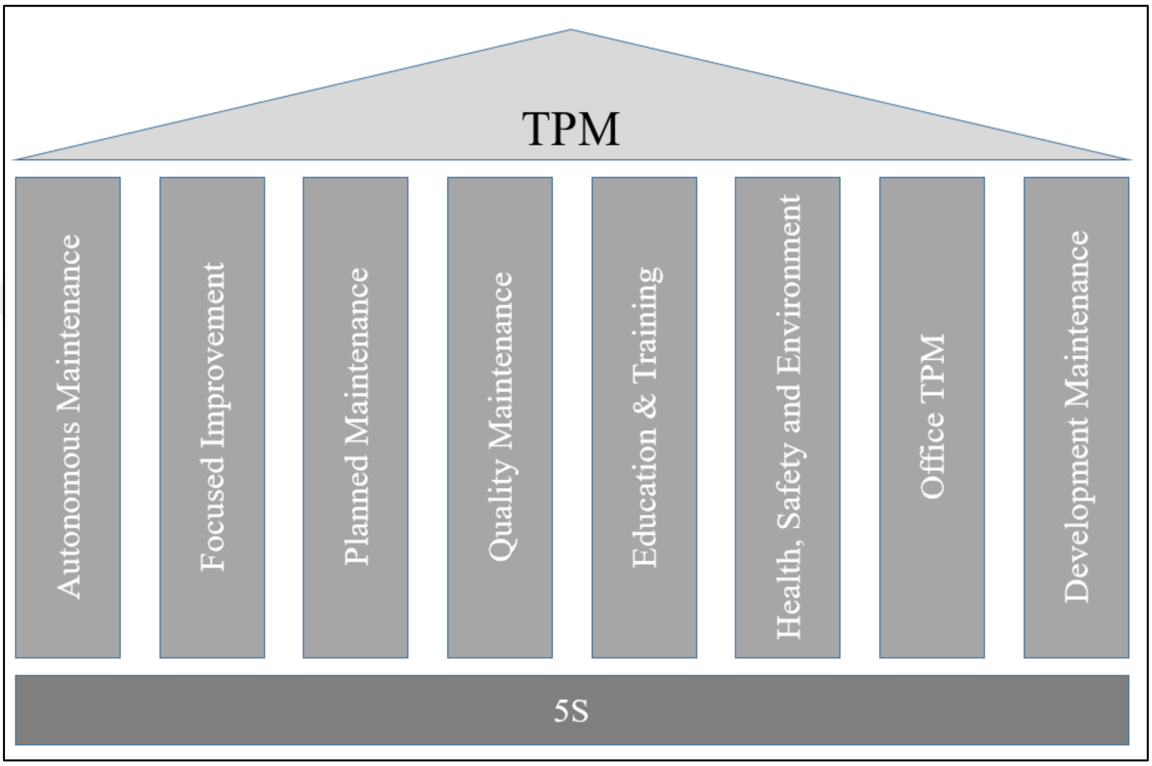

Fig. 2 Pillars of TPM (adapted from Ahuja and Khamba 2008)

According to these pillars, 5S is the basis of TPM. The principle says that problems cannot be recognized when the place is unorganized. Activities of 5S are respectively; Removing unnecessary items from the area (Sort), configuration of required items in an order to provide easy usage (Systematize), removing dirt and dust from the area by cleaning (Shine), keeping high standard of the organized area (Standardize), and training people to sustain same discipline autonomously (Sustain).

Main focus of Autonomous Maintenance (AM) pillar is to increase maintenance abilities and sense of ownership of the employees. AM principle says that there are two types of deterioration; natural and forced. AM aims removal of forced deterioration with upkeep of the equipment by skilled and responsible operators.

Focused Improvement (FI) is also known as Kaizen and means continuous improvement. Main objective of FI is to provide everyday better performance than previous day for the equipment. Key metric of FI pillar is Overall Equipment Effectiveness (OEE) and targets eliminating all losses. The principle of Kaizen says that it is a more effective way to make large number of improvements, but in small scale instead of a few large improvements.

Focus point of AM was eliminating forced deterioration. Moreover, Planned Maintenance (PM) aims to remove natural deterioration. Desired outputs of PM are extending technical life of the equipment, maximization of equipment availability, elimination of breakdowns or failures, and decrease on maintenance costs.

Main target of Quality Maintenance (QM) pillar is to sustain customer satisfaction through manufacturing without any defects. There are important activities such as eliminating non-conformances, existing quality concerns and potential quality concerns with a proactive way. Outputs of QM are to provide zero customer complaint, decrease process defects, and decrease quality cost.

It is important for Education and Training (E&T) pillar to ensure multi-skilling of employees. Main target is to have operators who are at expert level.

Health, Safety and Environment (HS&E) pillar involves all other pillars to provide a safe workplace without any accident, health damage or fires.

One of the main objective of Office TPM is improving synergy between various business factors. With the involvement of all functions, Office TPM pillar focuses to increase plant performance, remove procedural hassles, reduce manpower, and provide utilized, clean and pleasant work area.

Development Maintenance pillar aims to complete implementation of new equipment on time and with minimum problems by using learnings from existing systems.

2.6 Lean Maintenance (LM)

Lean Maintenance (LM) is a Toyota based proactive maintenance strategy applying Total Productive Maintenance (TPM) activities such as employing planned and scheduled maintenance, developed by Reliability Centered Maintenance (RCM) decision logic, and performed by skilled action teams using fundamentals of TPM pillars (Smith, 2014). LM aims to do required maintenance at the correct time. That means that main objective of LM approach is to perform maintenance activities in the most effective and efficient manner without any waste, failure or accident (Gupta et al., 2017). When the subject is “lean”, the most important principle is eliminating wastes, and Ohno (1988) categorized seven type of wastes in mass production which can also be discussed for maintenance in the same manner (Gupta et al., 2017; Mostafa et al., 2015; Davies and Greenough, 2013):

1. Over maintenance: Performing maintenance activity although equipment does not need at that time.
2. Waiting for maintenance resources: Means idle time that production department waits for maintenance crew including tools, documentation spare parts, permits, etc.
3. Transporting: When the maintenance store is centralized far from the job performed, that causes transportation waste since commonly used parts are not hold together and task sequencing for the machines are not available.
4. Task processing: Performing improper maintenance because of incorrect tool usage or poor product design.
5. Waste of inventory: It needs to be ensured that inventory contains needed material and spare parts, but not more.
6. Redundant motion: Unnecessary movement of maintenance team such as searching for spare parts, tools, documents, etc. Unnecessary periodic maintenance tasks are also part of motion wastes.
7. Defects: Caused by improper designs and maintenance practices including unneeded inspection, scrap, rework, etc.

Beyond any doubt, decrease of maintenance related wastes is essential for lean approach, but it is not the only single principle. Baines et al. (2006) claims that the definition of lean philosophy is evolving from eliminating wastes to value creation. Ayeni et al. (2011) also states that value creation seems to have bigger role comparing to waste elimination, however both are closely associated with each other and it is very important to consider both motivations in the industry.

3. LITERATURE REVIEW

In the previous section, the approach in historical development of maintenance management has been analyzed. As lean maintenance is the most productivity-oriented method used in the recent times, the scope of this thesis has been limited with Lean Maintenance. In this section, studies related with Lean Maintenance have been researched. Since this thesis uses Multiple Criteria Decision Making (MCDM) tool as research methodology, studies of maintenance management and multi criteria decision making tool have also been analyzed. Moreover, literature has been reviewed to examine gaps in the studies of Lean Maintenance management and execution of multi criteria decision making tool in Lean Maintenance management.

Baluch et al. (2012) discussed types of wastes that a company usually has during maintenance such as unproductive work, delays of motions, unnecessary motion, etc.; and stated that lean approach is essential to eliminate those wastes. The authors also mentioned that lean maintenance and lean manufacturing have different fundamentals and maintenance strategy must be built with the consideration of this fact. In the article of Arlbjørn and Freytag (2013), it has been stated that Arlbjørn et al. (2008) divided lean into three levels which are philosophy, principles, tools and techniques. Philosophy level states that lean aims to reduce waste and develop customer value. Principles level includes five principles of Total Productive Maintenance which are specifying what does create value from the customer's perspective, identifying all necessary steps to highlight non value adding waste, creating value flow without waiting or scrap, defining what is pulled by the customer, and removing related layers of waste as they are uncovered. Tools and techniques level includes lean methods such as 5S, value stream mapping, pull production, overall equipment effectiveness, continuous improvement, etc. Jasiulewicz and Kaczmarek (2014) presented integration of lean and green maintenance approach to increase profit of the company by reducing cost with eco-friendly practices such as minimizing usage of energy, raw material etc. In their study they considered manufacturing focus, strategy of inventory, choosing supplies, and product design. Shahrabi and Shojaei (2014) demonstrated an application of lean principles to improve maintenance management in a refinery by using Analytical Hierarchy Process (AHP) Method and Failure Mode and Effect Analysis (FMEA). Mostafa et al. (2015) mentioned that maintenance activities have a big share within the total production cost, and suggested a roadmap to eliminate maintenance related wastes in the organizations using multi-criteria decision making. In their study, the authors proposed a flexible lean maintenance roadmap to integrate lean principles with maintenance processes. There were five steps in their proposed roadmap. The first step was focusing on planning of maintenance and strategy. Secondly, maintenance performance metrics were defined such as overall equipment efficiency (OEE), mean time between failures (MTBF), and availability. In the third step waste analysis were done, and lean principles were applied in fourth step. After lean strategy was implemented and OEE was evaluated, standardization and pursuing lean practices were determined as key principles for the last step. Nhaili et al. (2016) discussed to design a strategy that measures maintenance performance and Overall Equipment Efficiency (OEE) by using lean improvement actions in an automotive supplier company. The authors presented relationship between maintenance activities and wastes, and proposed maintenance actions according to the importance of these actions. As a result of their study, OEE has been improved in the company. In the study of Ayeni et al. (2016), impact of lean on maintenance activities within the identified key characteristics of operation has been investigated. In their study, key characteristics were identified as structural and infrastructural ones. As a result of a survey performed with the involvement of professionals from the industry, it has been revealed that process and technology has the highest influence of lean in terms of structural characteristics. However, there were three infrastructural characteristics in high influence level with lean, and they are performance measurement, quality control, and human resources. Gupta et al. (2017) claimed that a metric is needed for maintenance leanness which includes all lean maintenance features. Accordingly, the authors identified lean maintenance features and link these features to evaluate the leanness of the organization. Eight lean maintenance features have been identified in the study to build lean maintenance framework and the importance of these features was evaluated according to the opinions of the authors. Gupta et al. (2017) presented a scoring method and framework to provide a review about the lean maintenance status of an organization. Sanchez and Sunmola (2017) discussed critical success factors influencing effectiveness of lean maintenance activities in aviation industry which has high maintenance costs in order to sustain safety and quality consistently. The authors analyzed those factors with a focus group consisted by aerospace engineers and identified importance of the success factors on the effectiveness of lean practices in traditional and cloud based maintenance activities in aviation sector. In the study of Shou et al. (2019), a guideline was presented to apply lean principles effectively in turnaround maintenance (TAM) activities in oil and gas industry. The authors determined value adding and non-value adding activities after defined wastes with lean approach, and they obtained a value stream mapping (VSM) analysis with the involvement of three focus group studies. Biedermann and Kinz (2019) discussed that there is a need for maintenance management as a part of asset management to develop a new lean concept which includes lean approach and smart maintenance principles. As indicated in their study, lean smart maintenance (LSM) is a learning maintenance management approach, and focuses on dynamic strategy adaption aiming to prevent failures. Biedermann and Kinz (2019) presented a LSM implementation model to build a more efficient asset management.

Despite the fact that MCDM methods have been rarely used for maintenance management, some of the studies analyzed the weight of the factors and system selection problems by using MCDM tools. Triantaphyllou (1997) discussed a maintenance decision making problem by applying Analytic Hierarchy Process (AHP) approach while various maintenance criteria are relatively determined by decision makers. Almeida (2001) argued maintenance planning for two problems which are repair contract selection and spares provisioning. The author used Multiattribute Utility Theory (MAUT) by considering response time and cost as variables, and presented the influence of maintenance planning on the increase of competitiveness. Garcia-Cascales and Lamata (2009) studied a problem of the selection of a cleaning system for pieces of four stroke engines. The authors used MCDM methods which are AHP and Fuzzy Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) to determine to select the best system according to decision makers' option. Sabaei et al. (2015) presented a general overview in terms of MCDM methods and guided to choose proper method for maintenance management according to the priorities and preferences of a company. The authors stated that selection of correct method is the most critical step for decision makers in maintenance management.

3.1 Gaps in the Literature and Contribution to the Study

There are very limited number of studies that focused on the framework of the roadmap to apply lean maintenance policy in the companies except for Gupta et al. (2017) and Mostafa et al. (2015). In addition, Ayeni et al. (2016) discussed the impact of lean within the key characteristics. However, the study of Ayeni et al. (2016) based on a questionnaire, and the results were only compiled of the opinions of the people involved to the survey. When we compare Gupta et al. (2017) and Mostafa et al. (2015), it is seen that Gupta et al. (2017) provided a framework to evaluate the level of leanness of the maintenance. On the other hand, Mostafa et al. (2015) proposed a roadmap in terms of lean thinking to eliminate maintenance related wastes by integrating lean principles into maintenance management. However, the study of Mostafa et al. (2015) did not provide any knowledge for the impact of lean factors on each other. Despite the fact that Gupta et al. (2017) presented the influence and importance of these factors, the authors did not provide sufficient and strong evidences about the relationship between these factors. Besides, many studies in maintenance management which are using MCDM techniques are about selecting maintenance system according to cost, reliability, repairability, availability, etc. There is no examination about the relationship between the factors of maintenance management according to the best of our knowledge. Most of these studies focused on using MCDM tools to choose an alternative system or approach for maintenance or repair problems. Hence, this study is designed to cover these deficiencies in the literature and aims to contribute as described below:

a) That is aimed to present the order of importance of the factors which affect lean maintenance management, and execute cause and effect relationship between these factors, based on evaluations of the experts.
b) This study is going to provide a strategic map of the important factors that should be considered in lean maintenance management. Hence, this map aims to provide managerial input and help practitioners to manage lean maintenance activities effectively.

4. RESEARCH METHODOLOGY

As discussed in the previous section; gaps have been identified in the literature and the scope of this study has been determined as analyzing the relationship within the factors which are effective in lean maintenance management systems, and building a roadmap for the professionals in the industry. The most detailed study related to this subject belongs to Gupta et al. (2017) who also developed a scoring to present lean maintenance level. The factors considered in this study are predicated on the study of Gupta et al. (2017), and explained as the following.

According to the framework presented by Gupta et al. (2017), organizational related processes are essential for a lean maintenance system as shown in Fig. 3. Some of the important business processes causing wastes are poor operating skills, unnecessary administrative procedures, inaccurate investment for maintenance tools, and improper working area. As these processes affect lean maintenance, proper business process is needed to achieve lean maintenance targets. It is seen that one of the ways of improvement is changing design for reliability improvement and error proofing. The other one is changing maintenance practices to eliminate wastes.

Gupta et al. (2017) stated eight features of lean maintenance system influencing wastes. There are management support including administrative processes, data collection, identification of equipment critically, planning, maintenance manpower resource, maintenance autonomation, inventory of spares and materials, tools and techniques to eliminate waste. Gupta et al. (2017) described these features as the following.

Management support is necessary to achieve LM targets in the organization. So it is important to know whether management supports maintenance philosophy or not. It should be considered that the quantity of supervision steps of maintenance. That is also important to know the support of administrative system to arrange maintenance manpower, spare parts, materials, tools and maintenance equipment easily.

That is also very important to collect proper and sufficient data for the implementation of LM requiring design changes. It needs to be enquired if there is a system to collect below data:

- Maintenance performed because of improper operation strategy
- Rework
- Waste of time due to maintenance

- Number of visit to stores
- Number of supervisory man-hours
- Transportation wastes
- Waste of time for searching items
- User complaints

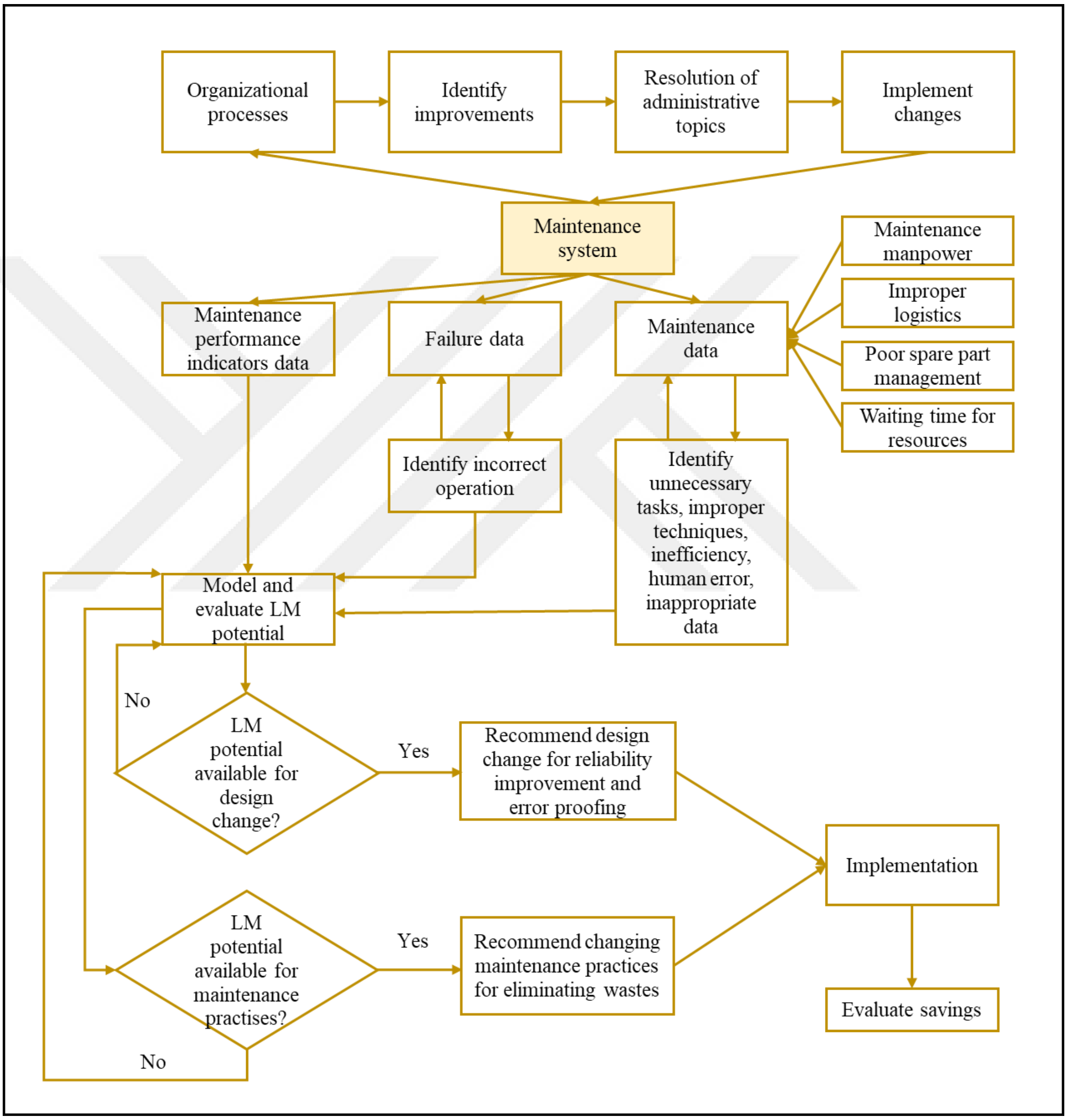

Fig. 3 Lean Maintenance System Framework (adapted from Gupta et al., 2017)

In order to prioritize equipment, equipment critically should be identified. This feature provide an opportunity to define which equipment need to be focused more. It is very important for an organization to know how create the biggest impact in the quickest way as the organization has no unlimited resources and need to use these resources wisely.

It needs to be ensured that maintenance planners are chosen from various departments; and transparency has been provided for maintenance planning document, manpower, materials and other resources. Effectiveness of planning group should also be evaluated.

According to Gupta et al. (2017), manpower is also a very important resource for the maintenance activity. During evaluation of the influence of this feature, below questions need to be considered:

- Is maintenance manpower self-directed or not?
- Does the crew have technical qualification and experienced in similar jobs?
- Do they have any physical or mental attributes?
- Do resources have multiple skills?
- Are they capable to analyze failures and decide that caused by design issue or external effects?
- Is the manpower involved into design team to make suggestions for decreasing maintenance requirements?
- Is the manpower a part of decision making mechanism to determine maintenance type and frequency?

Moreover, it is assumed that benefits of maintenance autonomation are eliminating rework, preventing defective maintenance, and focusing on the problems to not reoccur. It needs to be ensured that all processes for maintenance tasks are designed with error proofing system including proper jigs and fixtures to prevent wrong assembly. Equipment should also be designed in that direction.

Inventory of spares and materials is also critical to provide scheduling of spare parts, consumables and other materials at correct time when performing maintenance tasks. Organization also needs to have solid material supply chain to be in line with Just in Time (JIT) principles. Content and location of the store should be optimized to ensure avoiding wastes caused by unnecessary travel or spare part research.

Tools and techniques to eliminate waste are important to have solid reliability models for all equipment based on field data. Maintenance tasks should also be in line with ergonomic standards. Work place needs to be organized and managed with the direction of 5S technique.

As a conclusion of the study of Gupta et al. (2017), it has been decided that management support has the biggest impact on lean maintenance management of an organization. The authors also determined that identifying equipment critically, inventory management, and manpower resource are the following significant factors in terms of lean implementation. However, there was no evidence presented for the importance and influence levels of these factors. In this study, a systematic approach is used to evaluate cause and effect relations between lean maintenance features. Considering that it is required to have a multi criteria decision making process to be able to analyze the relationship within these features, and determine the importance and effectiveness of these factors based on experiences and knowledge of the experts chosen; it has been decided to evaluate these relations by using a Multi Criteria Decision Making (MCDM) method.

4.1 Fuzzy DEMATEL Method

Real world problems are affected by several criteria. Hence, various alternatives need to be considered and compared according to a number of different criteria. MCDM methods guides the organizations and executives to provide desired knowledge for various alternatives in a complicated decision making environment (Cascales and Lamata, 2009). There are several MCDM methods in the literature which enable to identify the importance of the alternatives according to the defined criteria, and the most commonly used techniques are AHP, TOPSIS, PROMOTHEE, ELECTRE, and DEMATEL (Sabaei et al., 2015). Within these methods, DEMATEL method is able to present cause and effect relation along defining rank according to the weights as the other methods. In this study, DEMATEL method is chosen to be able to evaluate the influences between several factors.

DEMATEL is the shortening word of “Decision Making Trial and Evaluation Laboratory” which was conducted by The Battelle Memorial Institute at first (Gabus and Fontela, 1972, 1973). DEMATEL method establishes and analyzes structural models which include cause and effect relations of various complex factors (Wu and Lee, 2007). DEMATEL method allows to divide factors into cause group and effect group. In simple terms, these groups indicate direct relations of the factors based on values which represent the strength level of influence. So the method builds a comprehensible structural model by explicating cause and effect relations between the factors (Chang et al., 2011).

In the implementation of DEMATEL method, there are five definitions need to be followed (Wu and Lee, 2007; Lin, 2013).

Definition 1: Direct relation matrix needs to be generated. Comparison scale is required for the level of influence which are represented as 0 (no influence), 1 (very low influence), 2 (low influence), 3 (high influence), 4 (very high influence).

Definition 2: Initial direction matrix $Z = [z_{ij}]_{nxn}$ is calculated for influences between the factors where z_{ij} represents the level of influence.

Definition 3: Normalized direct relation matrix X is determined.

$X = [x_{ij}]_{nxn}$ and $0 \leq x_{ij} \leq 1$

$$X = s \,.\, Z \quad (1)$$

$$s = \frac{1}{\max 1 \leq i \leq n \sum_{j=1}^{n} zij} \quad , \quad i,j = 1,2,\ldots,n. \quad (2)$$

Definition 4: Total relation matrix T is achieved, where I is identity matrix.

$$T = X\,(1 - X)^{-1} \quad (3)$$

Definition 5: Rows and columns of total relation matrix T are summed up separately.

$$T = t_{ij} \quad , \quad i,j = 1,2,\ldots,n \quad (4)$$

$$D = \sum_{j=1}^{n} t_{ij} \quad (5)$$

$$R = \sum_{i=1}^{n} t_{ij} \quad (6)$$

Due to the fact that there are many uncertainty in real world problems caused by goals, constraints or other variables; fuzzy set theory introduced by Zadeh (1965) is commonly used for that kind of studies (Seker and Zavadskas, 2017). In the studies which consider fuzzy evaluations of the experts, there are uncertain statements referring grey areas. So the decisions are not only composed of numbers like "0" or "1" (Feng and Ma, 2020). In the logic of fuzzy set theory; each number between 0 and 1 represents a partial truth which means partial degree of membership, whereas crisp sets correspond to binary logic [0,1]. So the logic presents unstable subjective judgements mathematically (Al-Najjar & Alsyouf, 2003). In order to convert these uncertain evaluations to clear numbers, triangular fuzzy number method is used in this study. In that method, fuzzy evaluations are expressed by triangular fuzzy number forms e.g. (0.25, 0.5, 0.75), and these numbers are defuzzified to clear values to be able to build a direct relation matrix (Feng and Ma, 2020). In the study of Opricovic and Tzeng (2003), it was stated that one of the defuzzification methods is Converting Fuzzy data into Crisp Scores (CFCS), and following equations (7–14) need to be used to convert fuzzy numbers into a crisp set with this method.

$z_{ij}^{k} = \left(l_{ij}^{k}, m_{ij}^{k}, r_{ij}^{k}\right)$ indicates fuzzy scores according to the experts' (k = 1,2,…,p) opinions.

(i) Normalization:

$$xl_{ij}^{k} = \left(l_{ij}^{k} - min\ l_{ij}^{k}\right) / \Delta_{min}^{max} \quad (7)$$

$$xm_{ij}^{k} = \left(m_{ij}^{k} - min\ l_{ij}^{k}\right) / \Delta_{min}^{max} \quad (8)$$

$$xr_{ij}^{k} = \left(r_{ij}^{k} - min\ l_{ij}^{k}\right) / \Delta_{min}^{max} \quad (9)$$

$$\Delta_{min}^{max} = \max r_{ij}^{k} - min\ l_{ij}^{k}$$

(ii) Calculate left (ls) and right (rs) normalized values:

$$xls_{ij}^{k} = xm_{ij}^{k} / (1 + xm_{ij}^{k} - xl_{ij}^{k}) \quad (10)$$

$$xrs_{ij}^{k} = xr_{ij}^{k} / (1 + xr_{ij}^{k} - xm_{ij}^{k}) \quad (11)$$

(iii) Calculate total normalized crisp value:

$$x_{ij}^{k} = \left[xls_{ij}^{k}\left(1 - xls_{ij}^{k}\right) + xrs_{ij}^{k} xls_{ij}^{k}\right] / [1 - xls_{ij}^{k} + xrs_{ij}^{k}] \quad (12)$$

(iv) Calculate crisp values:

$$z_{ij}^{k} = min\ l_{ij}^{k} + x_{ij}^{k}\ \Delta_{min}^{max} \quad (13)$$

(v) Integrate crisp values:

$$z_{ij} = \frac{1}{p}(z_{ij}^{1} + z_{ij}^{2} + \cdots + z_{ij}^{p}) \quad (14)$$

Wu and Lee (2007), proposed to follow four steps to implement DEMATEL method in a fuzzy environment based on experts' opinions. In the first step, goal of the decision and experts related to the issue need to be determined for further evaluation. Secondly, fuzzy linguistic scale should be designed and influencing factors must be established. In this study, a triangular fuzzy linguistic scale is used. Influence levels are represented as following; no influence (0, 0, 0.25), very low influence (0, 0.25, 0.5), low influence (0.25, 0.5, 0.75), high influence (0.5, 0.75, 1), very high influence (0.75, 1, 1) as shown in Table 2. In the third step, evaluations of the experts are acquired. Finally, a structural model is established according to the results obtained. By using formulas (5) and (6), a causal diagram is drawn where (D + R) indicates the importance sequence of the factors and (D – R) calculation determines whether the feature belongs to cause group or effect group. If the result (D – R) of is negative, it means that feature is in effect group. If it is positive, it can be told that the feature belongs to cause group.

Table 2 Influence Levels and Corresponding Fuzzy Scores (adapted from Feng and Ma, 2020)

Degree of Influence	Score	Triangular Fuzzy Scale
No influence	0	(0, 0, 0.25)
Very low influence	1	(0, 0.25, 0.5)
Low influence	2	(0.25, 0.5, 0.75)
High influence	3	(0.5, 0.75, 1)
Very high influence	4	(0.75, 1, 1)

4.2 Implementation of Fuzzy DEMATEL Study

In this study, experts have been chosen from the industry by taking into consideration their experiences in lean maintenance or lean manufacturing. It has also been considered to provide an evaluation by the experts who are in the different steps of their own career to have various perspectives in the study. All of the eight experts in the study are engineers, and have experience in different industries using lean principles to reflect a wide point of view for maintenance management. Details of the experts are shown in Table 3.

In the evaluation phase, a document including eight main features of lean maintenance was prepared and shared with the experts by e-mail or face to face meeting. Experts were asked to evaluate influence levels between all factors given below by using fuzzy linguistic scale. The evaluation of Expert 4 is given in Table 4 as an example. The other experts' opinions are provided in Tables 11-18 in the appendix.

F1: Management support including administrative processes

F2: Data collection

F3: Identification of equipment criticality

F4: Planning

F5: Maintenance manpower resource

F6: Maintenance autonomation

F7: Inventory of spares and materials

F8: Tools and techniques to eliminate waste

Table 3 Detailed Information of the Experts in the Study

Person	Graduation	Current Industry	Current Field	Previous Experiences	Sertificates Related to Lean Methodology	Years of Experience in the Industry
Expert 1	Manufacturing Engineer	FMCG	Manufacturing	Automotive	Six Sigma Green Belt	7
Expert 2	Mechanical Engineer	Agricultural Machinery	Management	Machining	N/A	43
Expert 3	Mechanical Engineer	Automotive	Manufacturing	Automotive	Six Sigma Black Belt A3 Problem Solving	15
Expert 4	Electrical Engineer	Aviation	Maintenance	Automotive	Toyota Production System	7
Expert 5	Mechanical Engineer	Retired	N/A	Heavy Machinery, Agricultural Machinery, Iron and Steel, Packaging	N/A	32
Expert 6	Electrical & Electronics Engineer	Automotive	Maintenance	Automotive	Toyota Production System A3 Problem Solving Toyota Way	5
Expert 7	Mechanical Engineer	Aviation	Manufacturing	Automotive	Six Sigma Green Belt	6
Expert 8	Mechanical Engineer	Consumer Durables	Management	Consumer Durables	N/A	42

Table 4 Linguistic Evaluation of Expert 4

(N: No, VL: Very Low, L: Low, H: High, VH: Very High)

	F1	F2	F3	F4	F5	F6	F7	F8
F1		H	H	H	VL	VL	VL	H
F2	N		VH	VH	L	VH	VH	L
F3	N	L		VH	H	VL	H	L
F4	VL	L	VL		H	VH	H	VL
F5	VL	H	VH	H		H	L	VH
F6	N	H	VL	VH	H		H	VH
F7	N	L	H	H	L	H		VL
F8	VL	H	H	L	VH	H	H	

As seen an example of one expert's in Table 6, linguistic evaluations were converted to triangular fuzzy numbers. Then, these numbers were defuzzified by using the equations 7–14 to obtain the initial direct relation matrix Z which is shown in Table 5. Thereafter, the direct relation matrix X was created as in Table 7 with the normalization of the initial direct relation matrix.

Table 5 Initial Direct Relation Matrix

Z	F1	F2	F3	F4	F5	F6	F7	F8
F1	0.033	0.850	0.588	0.821	0.704	0.588	0.646	0.588
F2	0.354	0.033	0.733	0.733	0.588	0.646	0.675	0.442
F3	0.325	0.529	0.033	0.733	0.558	0.529	0.792	0.383
F4	0.529	0.529	0.413	0.033	0.675	0.733	0.792	0.588
F5	0.471	0.617	0.646	0.763	0.033	0.588	0.471	0.558
F6	0.238	0.500	0.646	0.704	0.617	0.033	0.471	0.588
F7	0.383	0.529	0.617	0.558	0.529	0.558	0.121	0.588
F8	0.529	0.500	0.588	0.588	0.588	0.617	0.588	0.033

Table 6 Conversion of the Evaluation of Expert 4 to the Fuzzy Numbers

	F1			F2			F3			F4			F5			F6			F7			F8		
F1	0	0	0.25	0.5	0.75	1	0.25	0.5	0.75	0.5	0.75	1	0.75	1	1	0.75	1	1	0.5	0.75	1	0.5	0.75	1
F2	0	0.25	0.5	0	0	0.25	0.75	1	1	0.75	1	1	0.25	0.5	0.75	0.75	1	1	0	0.25	0.5	0	0.25	0.5
F3	0	0.25	0.5	0	0.25	0.5	0	0	0.25	0.5	0.75	1	0.5	0.75	1	0.25	0.5	0.75	0.25	0.5	0.75	0	0.25	0.5
F4	0.25	0.5	0.75	0.25	0.5	0.75	0	0.25	0.5	0	0	0.25	0.75	1	1	0.5	0.75	1	0.5	0.75	1	0.25	0.5	0.75
F5	0.5	0.75	1	0.5	0.75	1	0.75	1	1	0.75	1	1	0	0	0.25	0	0.25	0.5	0	0.25	0.5	0	0.25	0.5
F6	0	0.25	0.5	0.5	0.75	1	0.5	0.75	1	0.75	1	1	0.5	0.75	1	0	0	0.25	0	0.25	0.5	0	0.25	0.5
F7	0	0.25	0.5	0.25	0.5	0.75	0	0.25	0.5	0.5	0.75	1	0.25	0.5	0.75	0.5	0.75	1	0	0	0.25	0.5	0.75	1
F8	0	0.25	0.5	0.25	0.5	0.75	0.25	0.5	0.75	0.5	0.75	1	0.25	0.5	0.75	0	0.25	0.5	0	0.25	0.5	0	0	0.25

Table 7 Normalized Direct Relation Matrix

X	F1	F2	F3	F4	F5	F6	F7	F8
F1	0.000	0.176	0.122	0.170	0.146	0.122	0.134	0.122
F2	0.074	0.000	0.152	0.152	0.122	0.134	0.140	0.092
F3	0.067	0.110	0.000	0.152	0.116	0.110	0.164	0.080
F4	0.110	0.110	0.086	0.000	0.140	0.152	0.164	0.122
F5	0.098	0.128	0.134	0.158	0.000	0.122	0.098	0.116
F6	0.049	0.104	0.134	0.146	0.128	0.000	0.098	0.122
F7	0.080	0.110	0.128	0.116	0.110	0.116	0.000	0.122
F8	0.110	0.104	0.122	0.122	0.122	0.128	0.122	0.000

After building total relation matrix T in Table 8, D and R values were calculated according to the equations 4–6. By using D+R and D-R values as shown in Table 9; cause and effect groups were identified, order of importance of the factors was determined, and a causal diagram was drawn as seen in Fig. 4 accordingly.

Table 8 Total Relation Matrix

T	F1	F2	F3	F4	F5	F6	F7	F8	D
F1	0.487	0.814	0.804	0.938	0.828	0.815	0.850	0.733	**6.269**
F2	0.493	0.577	0.741	0.824	0.721	0.736	0.764	0.631	**5.486**
F3	0.460	0.636	0.566	0.776	0.674	0.674	0.739	0.584	**5.109**
F4	0.533	0.691	0.703	0.707	0.750	0.764	0.794	0.670	**5.612**
F5	0.512	0.689	0.723	0.826	0.610	0.724	0.727	0.648	**5.459**
F6	0.437	0.620	0.672	0.758	0.672	0.563	0.673	0.607	**5.002**
F7	0.462	0.627	0.670	0.736	0.659	0.668	0.585	0.608	**5.015**
F8	0.511	0.655	0.698	0.779	0.702	0.711	0.728	0.530	**5.313**
R	**3.895**	**5.309**	**5.577**	**6.344**	**5.615**	**5.655**	**5.859**	**5.010**	

Table 9 D+R and D-R Values, and Order of Importance

	F1	F2	F3	F4	F5	F6	F7	F8
D+R	10.165	10.794	10.686	11.956	11.074	10.657	10.874	10.323
D-R	2.374	0.177	-0.468	-0.732	-0.157	-0.653	-0.844	0.303
Order of Importance	8	4	5	1	2	6	3	7
Cause group	F1, F2, F8							
Effect group	F3, F4, F5, F6, F7							

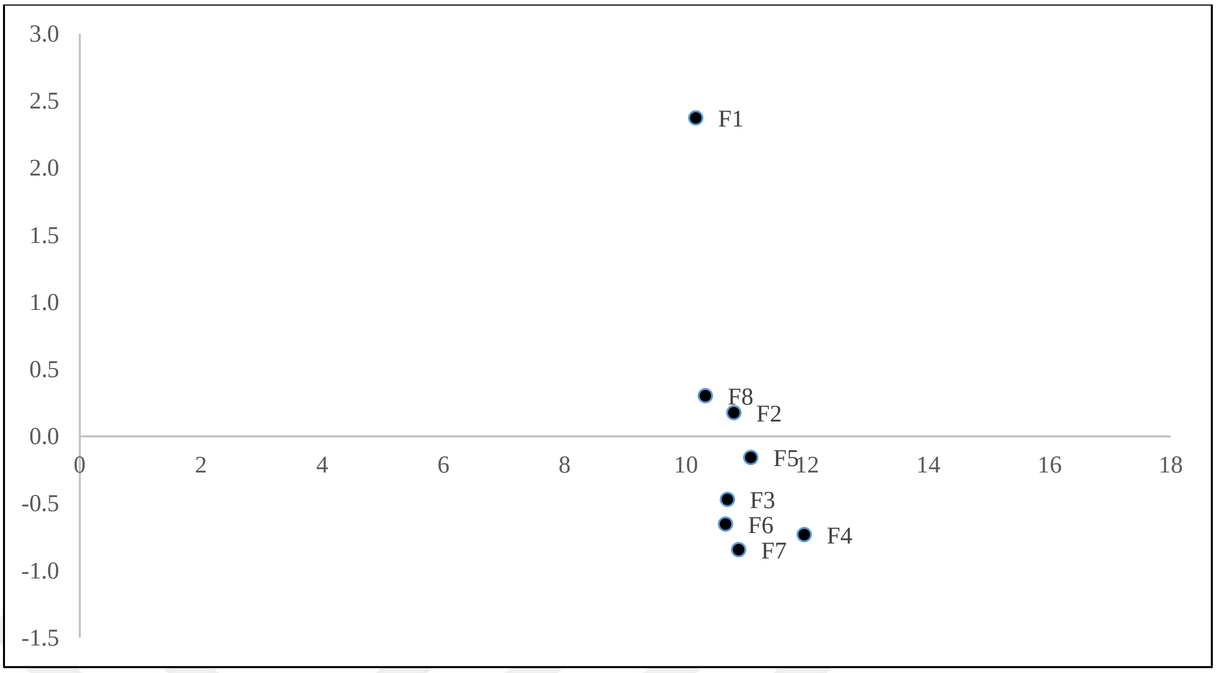

Fig. 4 Causal Diagram

According to the results obtained; the cause group for lean maintenance management which are above the x axis consists of management support including administrative processes (F1), data collection (F2), and tools and techniques to eliminate waste (F8) whereas the effect group (below the x axis) includes identification of equipment criticality (F3), planning (F4), maintenance manpower resource (F5), maintenance autonomation (F6), and inventory of spares and materials (F7).

According to our results, it is surprising to see that planning (F1) is the most important factor to accomplish lean maintenance activities. That is presumably because of the fact that if planning is not done properly, that causes wastes such as over maintenance, loss of spare parts, breakdown of the equipment, etc. The second important factor is maintenance manpower resource (F5). That is very critical to have a skilled manpower resource to perform effective lean maintenance. As the involvement of the team is essential for lean approach, the importance of manpower resource is also confirmed by the outcome of the study. The third important factor is determined as inventory of spares and materials (F7). Optimization of content and location of these materials is very critical to avoid wastes such as unnecessary travel or time loss for spare part research. Otherwise; data collection (F2), identification of equipment critically (F3), and maintenance autonomation (F6) have similar importance in terms of lean maintenance management.

The greatness of the number at the positive side of y axis shows the degree of influence of that factor. Besides, casual diagram states the affected factors at the negative side of y axis. According to the cause and effect relations, management support (F1) has the biggest impact on the other factors as seen in the casual diagram. As might be expected, the improvement of the other features is influenced by the support level of management in almost all organizations. Data collection (F2) and tools and techniques (F8) are also located in cause group, but they have slight impact on the other factors. When we check the affected factors, we see that maintenance manpower resource (F5) is the least affected factor by the other ones. It is strongly influenced by management support only, since management is the determinant of this factor normally. According to our experience it is not very surprising to see that the most affected factor is inventory of spares and materials (F7). Any failure on the other factors directly causes wastes on spares and materials. Rest of the factors in effect group (F3, F4, and F6) are similarly influenced by the others.

Even though Gupta et al. (2017) provided a framework to evaluate lean maintenance score for a typical company, they also briefly discussed the importance of these features without any evidence. According to their view, management support is the essential feature to build an effective lean maintenance management system. The second and the third ones are identification of equipment critically, and inventory of spares and materials. However; when we compare their thoughts with our findings, there are conflicting results. According to their view, management support is the most important factor whereas our finding shows that planning is the most critical one. Besides; according our results, identification of equipment critically is not one of the most significant factors, differently from Gupta et al. (2017). On the other hand, inventory of spares and materials has similar importance according to both results. The reason of these conflicts is that Gupta et al. (2017) evaluated these factors based on their own views. However, evaluations of the experienced experts were considered in this study. Moreover, these evaluations were analyzed with a scientific approach by using a multi criteria decision making method. Therefore, it is a normal and expected result to have this contradiction.

As a summary; features of lean maintenance were categorized as cause and effect groups, and prioritized according to their level of importance. With the knowledge of the relationship between these features, it is possible to provide a better understanding and propose reasonable suggestions. Cause and effect relation between these features, and order of importance need to be analyzed with caution to be able to guide organizations in the correct way. To present a more visual perspective and provide a managerial input for the professionals, a strategy map was drawn and interpreted in the following section.

4.3 Inferences and Observations of the Study

In the study, significant relationships between the factors in terms of lean maintenance management were presented based on a strategy map drawn to show these relationships in a structured way. As discussed in the study of Yang et al. (2008), average value of the total relation matrix T was calculated and determined as the threshold value α. In our study, threshold value α was 0.676, so the values above this number only were considered for the strategy map. A scale was obtained by dividing the values between minimum and maximum values in total relation matrix T into three groups. Minimum value above the threshold was 0.689, and the maximum was 0.938. Accordingly; values between 0.689 and 0.772 were described as medium; between 0.772 and 0.855 as strong, between 0.855 and 0.938 as very strong influence. To visualize these numbers, it was shown in Table 10 and remarked as **bold** for very strong, *italic* for strong, and underlined for medium influence. Different types of arrows were used to represent the degree of influence such as thick line for very strong influence, thin line for strong influence, and line with dashes for medium influence. Cause and effect groups were also indicated with grey and white boxes in the strategy map in Fig. 5.

Table 10 Influence Levels of the Factors above Threshold Value

T	F1	F2	F3	F4	F5	F6	F7	F8
F1	0.487	*0.814*	*0.804*	**0.938**	*0.828*	*0.815*	*0.850*	0.733
F2	0.493	0.577	0.741	*0.824*	0.721	0.736	0.764	0.631
F3	0.460	0.636	0.566	*0.776*	0.674	0.674	0.739	0.584
F4	0.533	0.691	0.703	0.707	0.750	0.764	*0.794*	0.670
F5	0.512	0.689	0.723	*0.826*	0.610	0.724	0.727	0.648
F6	0.437	0.620	0.672	0.758	0.672	0.563	0.673	0.607
F7	0.462	0.627	0.670	0.736	0.659	0.668	0.585	0.608
F8	0.511	0.655	0.698	*0.779*	0.702	0.711	0.728	0.530

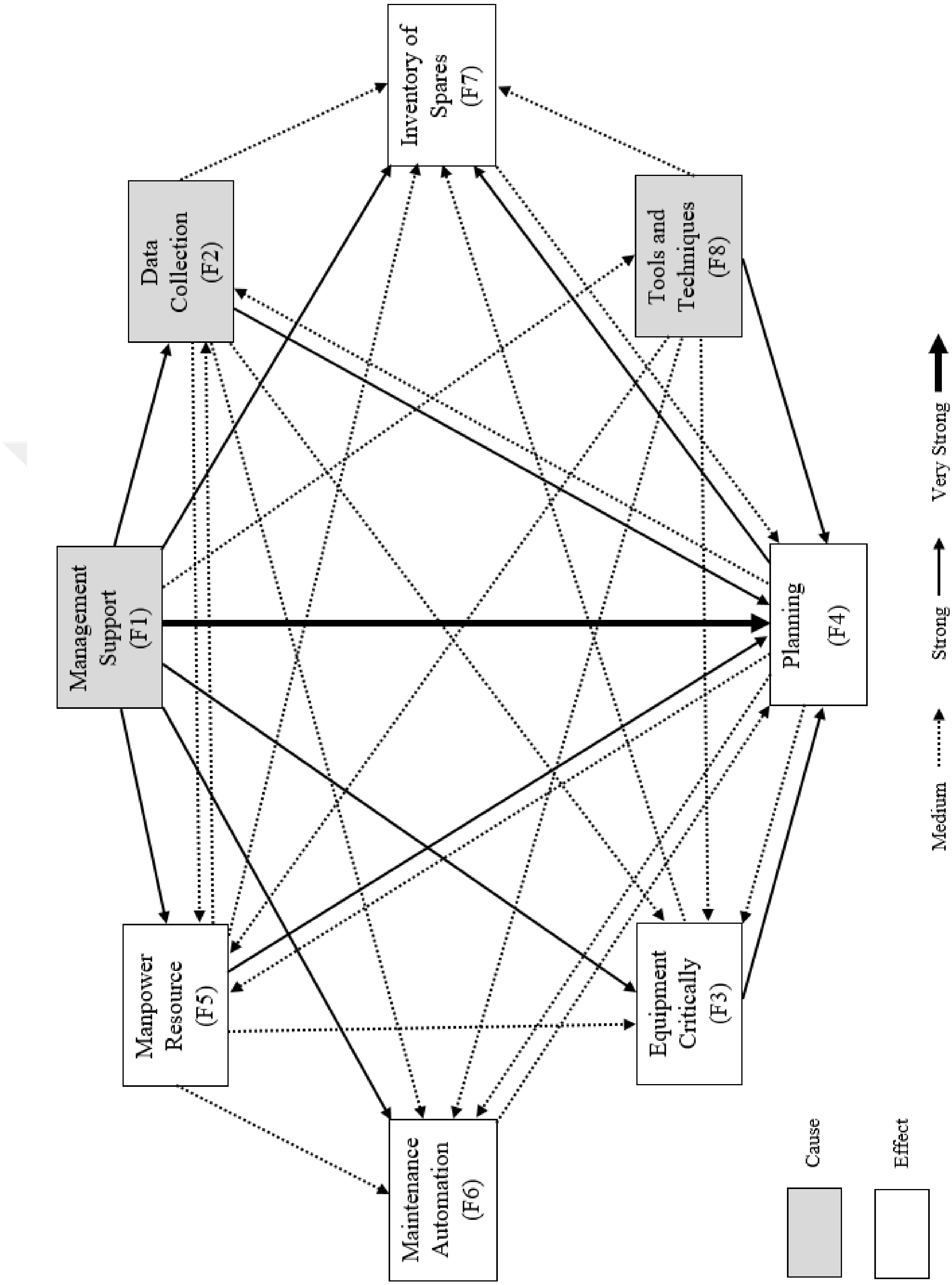

Fig. 5 Strategy Map

The results derived in the study aim to present a perspective for decision makers to perform an efficient and effective lean maintenance management. Therefore a strategy map was built to execute these results visually. According to the strategy map presented, there are a number of managerial insights derived to provide guidance to the practitioners in the industry. According to our findings; even though management support is the lowest important feature, it is the most influencer feature that causes the efficiency of all other features. Hence, the success of the other factors is strongly dependent on the management support. As known that, planning is the most important factor. However; according to the relationship in the strategy map, it is shown that the success of planning strongly depends on management support. At the same time, planning has a critical role since it is the most influenced factor by the others, especially by data collection, and manpower resource. As another significant implication of the strategy map, inventory of spares is a highly influenced factor in terms of lean maintenance, which is not a surprising result according to our experiences. If any failure occurs on the other affecting factors, spare part related wastes increases immediately. Another factor needs to be considered carefully is tools and techniques. This factor strongly influences planning which is the most important one. So it means that the tools and techniques used to eliminate wastes directly affect planning, and planning identifies the success of lean maintenance management.

5. CONCLUSION

In the study presented, casual relationship of lean maintenance factors were researched within defined limitations. These factors were considered according to the study of Gupta et al. (2017) to investigate cause and effect relations of them. Besides, views of eight experts were evaluated to execute these relationships. Views of the experts were quantitatively analyzed by using Fuzzy DEMATEL method.

One of the significant findings of the study was determining the order of importance of lean maintenance factors. According to the results, planning is the most important factor whereas management support including administrative processes is the least important one. As another outcome of the study, cause group of lean maintenance factors includes management support, data collection, and tools and techniques to eliminate waste. Besides; identification of equipment criticality, planning, maintenance manpower resource, maintenance autonomation, and inventory of spares and materials are the factors which belong to the effect group. Moreover, strategy map showed that management support strongly influences most of the factors. Inventory of spares and materials is the most affected factor by the others. According to the strategy map presented, managerial insights and suggestions were provided to the practitioners who desire to implement lean maintenance or improve the effectiveness and efficiency of lean maintenance management strategy.

This study could be expanded in such a way that the number of participant could be increased. In future studies, other features either from literature or practice could be considered in addition to the features defined by the study of Gupta et al. (2017). Moreover, contributions of the employees who physically perform maintenance activities could be provided to extend the scope of this study.

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APPENDIX

Table 11 Linguistic Evaluation of Expert 1

	F1	F2	F3	F4	F5	F6	F7	F8
F1		H	VL	VH	VH	H	H	H
F2	N		VH	H	VL	L	VH	N
F3	N	L		VH	L	H	VH	VL
F4	N	L	VL		H	H	VH	H
F5	N	VL	L	H		L	N	H
F6	N	L	H	H	H		VL	VL
F7	N	L	N	H	H	VL		N
F8	N	N	VL	L	L	VH	H	

Table 12 Linguistic Evaluation of Expert 2

	F1	F2	F3	F4	F5	F6	F7	F8
F1		H	L	H	VH	VH	H	H
F2	VL		VH	VH	L	VH	VL	VL
F3	VL	VL		H	H	L	L	VL
F4	L	L	VL		VH	H	H	L
F5	H	H	VH	VH		VL	VL	VL
F6	VL	H	H	VH	H		VL	VL
F7	VL	L	VL	H	L	H		H
F8	VL	L	L	H	L	VL	VL	

Table 13 Linguistic Evaluation of Expert 3

	F1	F2	F3	F4	F5	F6	F7	F8
F1		VH	H	H	L	H	VH	L
F2	H		VH	H	L	L	H	N
F3	L	H		L	N	N	H	N
F4	L	VL	N		N	H	L	L
F5	L	VH	VH	H		VH	L	H
F6	VL	N	H	L	VL		VL	VL
F7	VL	L	H	N	N	N		H
F8	VH	L	VH	VH	L	H	VH	

Table 14 Linguistic Evaluation of Expert 4

	F1	F2	F3	F4	F5	F6	F7	F8
F1		H	H	H	VL	VL	VL	H
F2	N		VH	VH	L	VH	VH	L
F3	N	L		VH	H	VL	H	L
F4	VL	L	VL		H	VH	H	VL
F5	VL	H	VH	H		H	L	VH
F6	N	H	VL	VH	H		H	VH
F7	N	L	H	H	L	H		VL
F8	VL	H	H	L	VH	H	H	

Table 15 Linguistic Evaluation of Expert 5

	F1	F2	F3	F4	F5	F6	F7	F8
F1		VH	H	VH	L	VL	VL	N
F2	VL		VL	N	H	L	H	VH
F3	N	H		L	VH	H	L	VL
F4	H	N	VL		L	VH	VL	L
F5	VL	L	N	VH		H	VL	N
F6	N	VL	L	H	H		VH	VH
F7	L	L	VH	N	VL	H		H
F8	VH	H	H	VL	N	N	L	

Table 16 Linguistic Evaluation of Expert 6

	F1	F2	F3	F4	F5	F6	F7	F8
F1		H	VL	VH	VH	VL	L	L
F2	L		VL	H	H	H	L	L
F3	VL	VL		L	L	H	VH	L
F4	L	L	VL		H	L	L	L
F5	VL	VL	VL	H		VL	VL	VL
F6	VL	L	H	L	H		H	L
F7	VL	VL	H	L	L	L		H
F8	VL	VL	VL	VL	L	L	L	

Table 17 Linguistic Evaluation of Expert 7

	F1	F2	F3	F4	F5	F6	F7	F8
F1		VH	H	H	L	L	H	H
F2	VL		H	H	L	VL	H	L
F3	H	H		H	L	VL	H	H
F4	H	VH	VH		H	L	VH	H
F5	H	H	VH	H		H	VH	VH
F6	L	L	L	L	L		H	H
F7	H	H	H	VH	VH	H		H
F8	H	L	H	H	VH	H	H	

Table 18 Linguistic Evaluation of Expert 8

	F1	F2	F3	F4	F5	F6	F7	F8
F1		VH	H	H	VH	VH	VH	H
F2	H		H	VH	VH	H	H	H
F3	H	L		VH	L	VH	VH	L
F4	VH	VH	VH		VH	H	VH	VH
F5	VH	H	L	L		L	L	L
F6	L	H	VH	H	L		H	H
F7	VH	H	H	H	H	H		H
F8	H	H	L	H	H	VH	H	