Development of a multi-objective methodology to select lean initiatives and weighted leanness measurement methodology in modular manufacturing companies

A Thesis submitted by

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Abstract

The survival of manufacturing organisations in today's competitive market depends on the quality of products and services, effectiveness of manufacturing operations, cost and waste reduction, and profit and market share growth. In this respect, one of the most established and well-known tools are lean manufacturing practices. The decision of selecting the most appropriate lean initiatives to adopt and apply in the production process while preserving cost and time benefits is a challenging task for most companies. Therefore, a multi-objective methodology that considers the impacts of each lean strategy on identified critical performance metrics and manufacturing wastes is proposed through this research. The results from the developed methodology in this research suggest the best set of lean initiatives for improving the most critical performance metrics and reduce non-value activities (wastes). The proposed methodology also provides more accurate results in suggesting a set of lean tools compared to the previous methods as it considers more than one factor.

Moreover, this research further extends the most recent leanness assessment model by developing a methodology that considers the interdependent relationships between lean performance metrics to provide an overall leanness index. Several research studies developed leanness assessment models, however, in these studies different performance metrics were considered to be equally important. In contrast, this research developed a weighted leanness measurement methodology. This was achieved through assigning relative importance weights to each performance metric based on competitive strategies when measuring the integrated leanness score.

A local modular construction company was used for this research to validate and show the effectiveness and efficiency of the developed methodologies. Furthermore, one of the suggested lean initiatives from the proposed methodology was adopted and implemented and the leanness score of the company was measured before and after the lean application using the weighted leanness measurement.

Through this research, the developed methodology for selecting lean initiatives and the weighted leanness measurement approach are used to advance the current knowledge of lean manufacturing by providing more accurate results from both methodologies.

Certification of Thesis

This thesis is entirely the work of *Saba Shams Bidhendi* except where otherwise acknowledged. The work is original and has not previously been submitted for any other award, except where acknowledged.

Student and supervisors' signatures of endorsement are held at USQ.

Dr Steven Goh

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Nomenclature List

$C_{A_{0i}}$	Amortisation cost without lean implementation
$C_{A_{1i}}$	Amortisation cost of implementing a lean strategy
$C_{A_{2ij}}$	Amortisation cost due to forced changes by implementing two inter-dependent lean strategies
$C_{O_{0i}}$	Operating cost without lean implementation
$C_{O_{1i}}$	Operating cost of implementing a lean strategy
$C_{O_{2ij}}$	Operating cost due to forced changes by implementing two inter-dependent lean strategies
$C_{R_{0i}}$	Risk cost without lean implementation
$C_{R_{1i}}$	Risk cost of implementing a lean strategy
$C_{R_{2ij}}$	Risk cost due to forced changes by implementing two inter-dependent lean strategies
$C_{V_{0i}}$	Variable cost without lean implementation
$C_{V_{1i}}$	Variable cost of implementing a lean strategy
$C_{V_{2ij}}$	Variable cost due to forced changes by implementing two inter-dependent lean strategies
D	Customer demand
L_i	Representation of i^{th} lean strategy $i = (1, 2, 3, \ldots)$
L_j	Representation of j^{th} lean strategy $j = (1, 2, 3, \ldots)$
L_{ik}	Representation of a lean strategy which improves multiple performance metrics at the same time
L_{iz}	Representation of a lean strategy which reduces multiple manufacturing wastes at the same time

$L_{ijkz}x$	Lean range for positive performance metrics
$L_{ijkz}y$	Lean range for negative performance metrics
$M_{g_i}^j$	The triangular fuzzy number of the j^{th} extent analysis of the i^{th} object
P_k	Perceived effectiveness value due to implementing a lean strategy which improves multiple performance metrics at the same time
P_z	Perceived effectiveness value due to implementing a lean strategy which reduces multiple manufacturing wastes at the same time
P_{0i}	Perceived effectiveness value without implementing lean strategy
P_{1i}	Perceived effectiveness value due to implementing i^{th} lean strategy
P_{2ij}	Perceived effectiveness value of implementing interrelated lean strategies
PM_{0_i}	Perceived value effectiveness of improving performance metrics without implementing lean strategy
PM_{1_i}	Perceived value effectiveness of improving performance metrics due to implementing lean strategy
PM_{2ij}	Perceived value effectiveness of improving performance metrics due to implementing two interrelated lean strategies
PW_{0_i}	Perceived value effectiveness of reducing manufacturing wastes without implementing lean strategy
PW_{1_i}	Perceived value effectiveness of reducing manufacturing wastes due to implementing lean strategy
PW_{2ij}	Perceived value effectiveness of reducing manufacturing wastes due to implementing two interrelated lean strategies
S_i	The value of fuzzy synthetic extent with respect to the i^{th} object
S_{ijkl}	Similarity value of consecutive performance values

T	Takt time
T_a	The net time available for manufacturing process
$T_{D_{0i}}$	Development time required for the current production process without implementing lean strategy
$T_{D_{1i}}$	Development time required for implementing a lean strategy
$T_{D_{2ij}}$	Development time required due to forced changes by implementing two interrelated lean strategies
$T_{P_{0i}}$	Planning time required for the current production process without implementing lean strategy
$T_{P_{1i}}$	Planning time required for implementing a lean strategy
$T_{P_{2ij}}$	Planning time required due to forced changes by implementing two interrelated lean strategies
$T_{T_{0i}}$	Training time required for the current production process without implementing lean strategy
$T_{T_{1i}}$	Training time required for implementing a lean strategy
$T_{T_{2ij}}$	Training time required due to forced changes by implementing two interrelated lean strategies
$T_{V_{0i}}$	Validation time required for the current production process without implementing lean strategy
$T_{V_{1i}}$	Validation time required for implementing a lean strategy
$T_{V_{2ij}}$	Validation time required due to forced changes by implementing two interrelated lean strategies
$V(M_2 \geq M_1)$	The degree of possibility of triangular fuzzy number
W	Normalised priority weighting of the performance metrics

W'	Weightings vector of the performance metrics
a_{ijkz}	Lower end point of triangular fuzzy number
b_{ijkz}	Vertex of triangular fuzzy number
c_{ijkz}	Upper end point of triangular fuzzy number
d_l	Difference value of consecutive data of each performance metric
lp_j	Lean performance measures, $j = (1, 2, \ldots, m)$
$p(i)$	Failure probability due to implementing lean strategy
pm_k	Lean performance metrics, $k = (1, 2, \ldots, n)$
s_i	Situation in the manufacturing organisation, $i = (1, 2, \ldots, t)$
μ_{ijkl}	Membership value of each performance metric

Publications

Journals

1. Shams Bidhendi, S, Goh, S., Wandel, A., Development of a weighted leanness measurement method in modular construction companies (Journal of Manufacturing Science and Engineering: Review completed)

Conference

1. Shams Bidhendi, S, Goh, S., Wandel, A., A multi-objective methodology for selecting lean initiatives in modular construction (20th International Conference on Advanced Manufacturing Engineering and Industrial Automation: Published).

Chapter 1: Introduction

The background and research motivation, research questions and objectives are explained in this chapter. The research significance and the thesis outline will also be explained.

1.1 Background

Lean manufacturing is an integrated approach that focuses on the elimination of different types of waste (such as wastes in human effort, time, inventory, market and production plant space) within the production process. Lean manufacturing is an operation management philosophy that aims to deliver high-quality products and services on time and with competitive prices to satisfy customers (Papadopoulou & Özbayrak 2005). The lean production system originated from the Toyota company, however, it is now widely recognised and used by enormous manufacturing firms to obtain the potential benefits of lean philosophy (Ohno, 1988).

Compared with mass production, lean production employs less resources, such as manufacturing plant, space, time, investment, design activities, on-site inventory level, etc., to deliver a similar product with the same level of quality in the most economical and efficient manner (Womack & Jones 1990; Bayou & Korvin 2008; Anvari et al. 2011). In addition, according to Shah and Ward (2007), lean production is an integrated socio-technical system that eliminates manufacturing wastes and controls the variability of suppliers and customers. Hence, if this manufacturing philosophy was adopted and implemented prudently, it could lead to global manufacturing excellence, transforming the production line into a high-quality system that delivers the final product to the customer on time and with minimum amount of wastes (Shah & Ward 2003; Papadopoulou & Özbayrak 2005).

1.1.1 Historical development of lean tools selection approaches

Selecting and implementing the appropriate lean tools to achieve the desired results is an important task for manufacturers. Not all lean strategies produce the same results and are suitable for every manufacturing enterprise and production problem (Browning & Heath 2009; Koukoulaki 2014; Havardell 2015). Although there are several success stories, many lean implementation projects failed due to the misapplication of various lean tools in terms of choice of appropriate lean strategy and misunderstanding of the context of applying the selected tools. Failure to apply and implement appropriate lean strategies leads to increased inefficiency in the production line and a reduction in labour productivity (Tiwari et al. 2007). Therefore, every section of the company requires different techniques and implementation strategies, which must be selected using appropriate methods to effectively address the organisation's problem (Wan & Chen 2008; Jing & Chang 2015).

Therefore, researchers have developed several lean methodologies and approaches for selecting the most appropriate lean techniques to eliminate manufacturing wastes and improve production performance (Prasad 1995; Hines & Rich 1997; Herron & Braiden 2006; Tiwari et al. 2007; Inanjai & Farris 2009; Alsyouf et al. 2011; Amin & Karim 2013). These performance metrics indicate the direction of changes from the current situation to the future state (Ramesh & Kodali 2012). In these methodologies, manufacturing wastes and sometimes performance metrics were ranked and the best set of lean strategies were advised based on these rankings. After implementing the selected lean tools, they measured the savings achieved in this journey and compared that to the initial measurements.

However, each lean strategy leads to specific results and has an effect on particular wastes and performance metrics. It is essential to consider the relationship of each lean tool on the performance metrics and identified wastes to select the best lean strategies and avoid incorrect application of lean strategies (Wan & Chen 2008). In this regard, several research studies were conducted to develop different methodologies for selecting lean strategies according to each organisation's requirements. In a few published methods, the relationships between lean tools and manufacturing wastes were considered to select the most appropriate lean strategies to minimise production problems and effectively improve performance (Amin, 2012). However, these available methodologies lack an effective approach that considers the relationship between lean tools, the identified manufacturing wastes, and performance metrics to suggest the most appropriate lean strategies to address both the critical performance metrics and wastes.

1.1.2 Methodologies for measuring the leanness index

After selecting appropriate lean tools and implementing them, it is important to understand the effects of these tools on the performance of the organisations, which emphasise the need for an appropriate methodology to measure the overall leanness score. Leanness index provides a direction to eliminate or at least reduce manufacturing wastes during the implementation of lean strategies through continuous improvement. It also indicates the improvement achieved during the lean journey (Papadopoulou & Özbayrak 2005; Anvari et al. 2011). In this regard, the leanness is defined by researchers in different ways. According to Wan and Chen (2008), the leanness is the stream-lined performance level in comparison with the optimum level (Wan & Chen 2008). Therefore, the reason for the failure of many of the current lean implementation practices is the lack of an appropriate method to measure and monitor the leanness levels before and after the implementation of lean strategies. Thus, the leanness measure models provide a tool to track, assess and compare the leanness level of the organisation during lean manufacturing transformation (Soriano-Meier & Forrester 2002; Behrouzi & Wong 2011).

To measure the leanness score of the organisation, several research studies identified factors for assessing leanness. These factors reflect the quality or quantity of the production process. Linguistic terms are used to evaluate the qualitative factors and numerical terms are used for quantitative factors. Currently, several research studies considered qualitative metrics to measure the leanness level (Vinodh & Chintha 2010; Taj & Morosan 2011; Vinodh & Chintha 2011; Vimal & Vinodh 2012) and some others used quantitative factors in their methods (Wan & Chen 2008; Amin 2012). In the current literature, the relationships between lean performance metrics were considered equal and the importance of these factors was considered equal to measure the leanness level of the organisation. Therefore, there is a gap in the literature that one should prioritise different performance metrics based on the manufacturers' requirements and include the interrelationship between lean performance metrics in the current leanness assessment models. This can increase the accuracy of the leanness assessment approach and reflect the manufacturers' needs in the overall leanness score.

1.2 Research gaps and questions

Several research studies and lean experts aimed to develop lean strategies and techniques to decrease non-value-adding activities, however, it is challenging to select the most effective lean tools to improve manufacturing performance and overall leanness of the company. A methodology for selecting the best set of lean tools should be developed to avoid an increase in non-value-adding activities caused by incorrect selection of these lean tools. Thus, suggesting proper application of lean tools that have a significant impact on improving performance metrics and manufacturing wastes is vital for manufacturers.

Many manufacturers choose lean strategies based on their personal judgments without any logical assessment of their sub sequential effects. Therefore, in order to achieve the desired results from the lean transformation, it is essential to develop a methodology that suggests the most effective lean tools according to their interrelationships with production problems and performance metrics. The selected lean tools should result in optimising the improvement of performance metrics and the reduction in manufacturing wastes. This research will attempt to establish an interrelationship between lean tools, manufacturing wastes and performance metrics for selecting the best lean tools to answer question 1 as described below.

Nowadays, many researchers understand the significance of the numerical approach to measure the leanness index of organisations and compare the value before and after the implementation of lean strategies.

Many research studies in this area attempted to measure the leanness score of each performance metric independently. However, few researchers were able to synthesise these leanness values into an overall leanness index by using various techniques, such as fuzzy logic to solve uncertain and complex problems. This is because individual performance metrics measured independently cannot accurately reflect the leanness level of an entire organisation.

Furthermore, to integrate the leanness level of performance metrics and measure the overall leanness, an equal interrelationship between these indicators was assumed by several researchers. However, fluctuation of one metric could have an effect on other metrics and consequently on the overall leanness level. Therefore, considering these interrelated impacts and the relative importance of performance metrics in the overall leanness measurement models can assist manufacturers in assessing the leanness index more accurately (Wong et al. 2012). In addition, assigning weightings for lean performance metrics can reflect an organisation's requirements more accurately (Wan & Chen 2008). This research will attempt to answer question 2 as described below, by developing a mathematical model based on fuzzy set theory to allocate weightings to each performance metric.

Two research questions were raised to achieve the overall research objectives, and these are:

- ***Question 1. How to select the proper set of lean strategies based on the interrelationships between different lean tools, performance metrics, and manufacturing wastes***?
- ***Question 2. How to develop a weighted leanness measurement method by considering the interdependent relationships between performance metrics?***

1.3 Objectives

The main objectives of this research are:

Objective 1: Developing a mathematical methodology for suggesting the best set of lean tools according to the interrelationships between lean techniques, performance measures and production wastes (Chapter 3):

This consists of establishing the relationship between lean tools, manufacturing wastes and, performance metrics and identifying the most critical performance metrics and manufacturing wastes that require improvement through the lean journey. This relationship will utilised to finally develop a mathematical model that considers interrelationships between lean tools, performance metrics and manufacturing wastes to select the most appropriate lean strategies.

Objective 2: Developing a weighted leanness assessment methodology to measure the overall leanness score using fuzzy logic as well as identifying the optimum leanness score for the specific manufacturing performance (Chapter 4):

For this objective, the first step is to establish the interrelationship between lean performance metrics to develop a weighted leanness measurement methodology using the fuzzy theory that considers the interdependent relationship between performance metrics. this can then be used to assess and provide more accurate overall leanness index for the organisation.

A real-life case study will be conducted to validate the proposed models and methodology in Chapters 3 and 4.

1.4 Significance of the research

The significance of this research is to develop a matrix illustrating the correlation between lean strategies, manufacturing wastes and performance metrics. The developed matrix can be used as a guideline for the lean practitioner by considering the effects of the lean tool and its sustainability for identified critical performance metrics and manufacturing wastes. In addition, a mathematical model that considers the relationship between lean tools, performance metrics and, manufacturing wastes is developed in this research with the aim of selecting the most appropriate set of lean strategies to achieve the highest perceived value.

Furthermore, this research develops a methodology that measures the overall leanness score of the organisation. In this methodology, fuzzy numbers are used to deal with uncertainties and vagueness. This method provides a more accurate overall leanness score of the selected production performance by establishing the interdependent relationships between lean performance metrics.

In conclusion, this research proposed a methodology that selects the most appropriate lean strategies for the selected production line and measures the overall leanness score more accurately before and after lean implementation.

1.5 Thesis outline

The thesis outline and the content of each chapter are presented as follows:

Chapter 2: Literature review

The wide range of literature on lean manufacturing philosophy is reviewed and analysed critically in this chapter. This chapter covers the most significant lean initiatives that have been applied during lean implementation journeys as well as various types of manufacturing wastes. Also, previous analytical and methodological approaches developed for selecting lean strategies were analysed. Moreover, the review of the leanness assessment models is presented critically. The objective of this chapter is to present a proper understanding of the research background and identify any existing research gaps.

Chapter 3: Development of a multi-objective methodology for selecting lean tools in manufacturing companies

This chapter explains the methodology developed to select lean strategies according to their impacts on manufacturing wastes and performance metrics. It also presents the development of the interrelationship matrix between lean tools, manufacturing wastes and performance metrics based on the literature review. Then, the methodology is developed to select the best set of lean strategies. The suggested lean tools will have the highest impacts on critical performance metrics and manufacturing wastes. Finally, a case study approach is used to validate and illustrate the effectiveness of the proposed methodologies and is also presented in this chapter.

Chapter 4: Development of a weighted fuzzy-based leanness assessment model

A novel leanness measurement methodology that uses fuzzy logic as well as a weighted method to include the relative importance of each performance metric in the lean measurement model will also be developed and discussed in this chapter. This model integrates both qualitative and quantitative performance metrics. Historical data were used to measure each performance metric and articulate these numbers into triangular fuzzy memberships. Then, the relative importance weights were allocated to each performance metric, which illustrates the interrelationship between these metrics. Finally, an overall lean score is measured based on data and weightings to present a more accurate score of the leanness level of the organisation. This model is used in a real-life case study at the end of this chapter.

Chapter 5: Conclusion, limitations and, future directions

Finally, a brief discussion of the research outcome, limitations and recommendations for future research are presented in this chapter.

Chapter 2: Literature review

This chapter provides a review and explains the main body of the extant literature on lean manufacturing. This extensive literature review will aid in the better understanding of the research gaps, aim and objectives.

2.1 History of the lean production system

After World War II, manufacturing companies were faced with a significant shortage of material, labour, and financial resources. Therefore, Japanese manufacturers had the challenge of competing with their American and western counterparts. In this respect, in order to deal with the several manufacturing problems and improve the production performance, Japanese leaders in the Toyota company developed a new process-oriented system, known as the Toyota Production System (TPS) or Lean manufacturing. The Toyota Production System (TPS) was known as a substitute for mass production systems to deal with many problems such as resource shortage, and customer demand for a large variety of products. Waste reduction during the operations process became the objective to survive resources shortages. Toyota leveraged the high efficiency of TPS to become sustainable and prosperous despite the lack of resources during the global economic crisis of North America in 1973 (Womack & Jones 1990; Conti et al. 2006).

From 1945 to 1970, Toyota Production System was well-known and growing across the world as a system that aims to minimize resources consumption and add value to the final product/service. To compete with Japanese manufacturing companies, lean manufacturing systems have been recognised and implemented by western manufacturers.

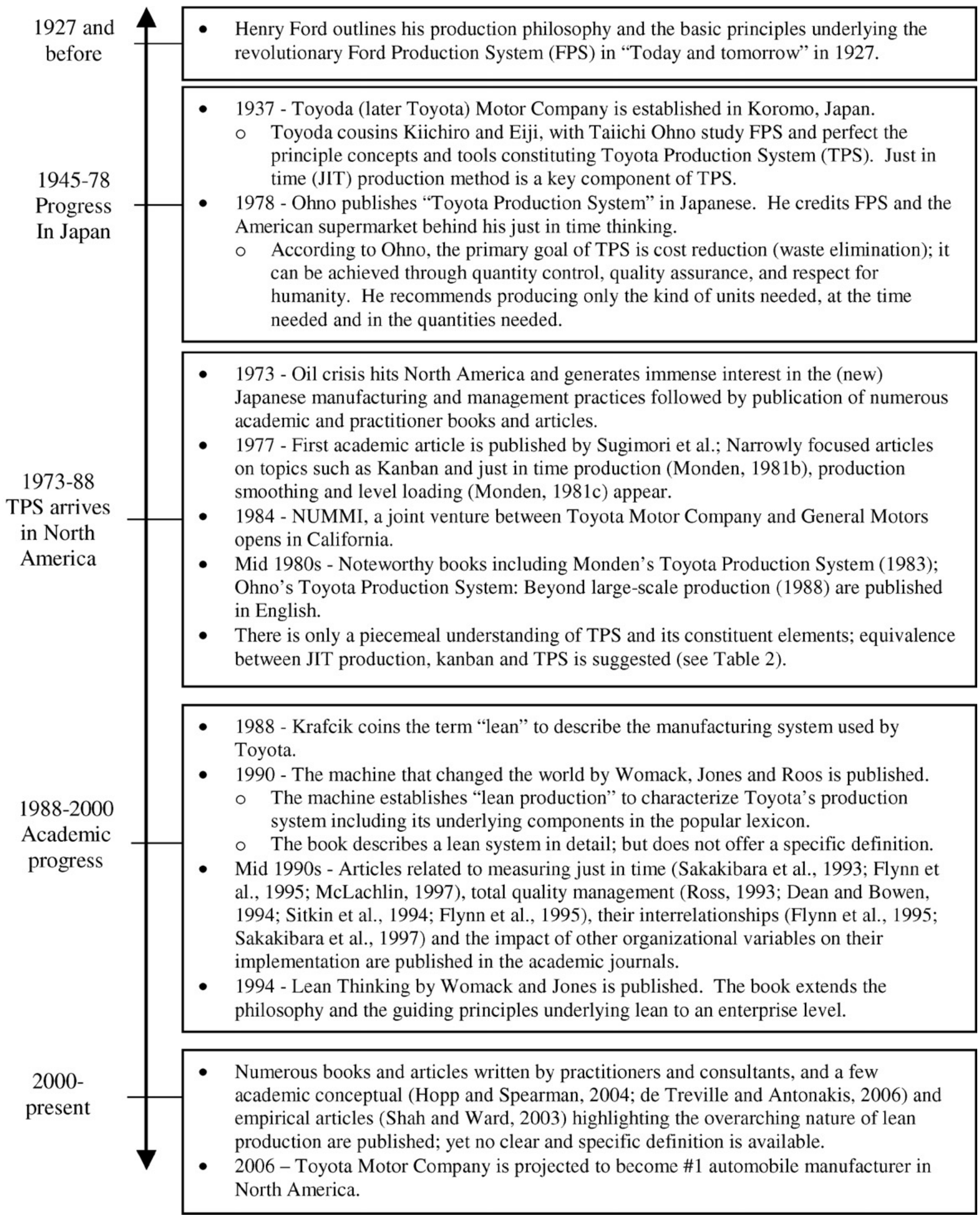

Figure 2.1: the critical phase of lean production timeline (Shah & Ward 2003).

2.2 Lean manufacturing initiatives and techniques

In several research studies on lean manufacturing, numerous lean initiatives have been developed to minimise particular wastes in the production line and improve their manufacturing practices. These tools and techniques assist the manufacturing organisation to become leaner by addressing various types of wastes (Shah & Ward 2007; Tiwari et al. 2007). However, it is essential to implement the most appropriate set of lean tools that match the requirements of the company. In this research, the lean tools are selected based on literature findings (Abdullah 2003; Shah & Ward 2003; Amin & Karim 2011): 5S, Total Quality Management (TQM), Total Productive Maintenance (TPM), Single Minute Exchange of Die (SMED), Just-In-Time (JIT), Production Smoothing, Kanban, Standard Work, Visual Control, Cellular Manufacturing, Safety Program, and Information Management System were the techniques found in the literature. A summary of these techniques is provided below:

5S

This technique helps manufacturers to improve productivity, reduce manufacturing cost, reduce lead time improve space limitations and reduce safety issues through five steps. These steps are 1) sort, 2) set in order, 3) shine, 4) standardise and 5) sustain the production process. (Chapman 2005). This technique has five main steps as discussed below (Zhou & Zhao 2010):

- *Sort:* in this step, all tools, materials, and equipment in the manufacturing line are reviewed and only essential ones are retained. This can help to reduce undesirable effects on the production line.
- *Set in order:* this step focuses on the order and arrangement of the organisation, where all items are labelled clearly to improve the efficiency in accessing them and to improve workflow.
- *Shine:* this step emphasises regular and systematic cleaning work to bring back the workstation to an appropriate condition at the end of operations. This method can help the operator find the required tools and equipment when starting a new shift and maintain the cleanliness and tidiness of the work area.

- *Standardise:* this step helps the manufacturer to make the first three S's a regulation and standardise them to be followed by all staff working in the company's production line.
- *Sustain:* once the four previous stages are completed, they become a habit and a part of the organisation's culture. This step helps the company to sustain the previous steps.

Some benefits of the 5S technique include reducing the waiting time (which is wasted by finding tools and materials), maintaining the cleanliness and tidiness of the workplace. which can enhance the safety of employees, and improve the reliability of the machines.

Just-In-Time (JIT)

JIT is a production method that designs the production process idealistically to decrease the inventory level to near zero and provide the required parts and products for the workstations on time (Detty & Yingling 2000). JIT is a management model that improves the elimination process of particular wastes (such as waiting time and overproduction). In this method, the manufacturing lead time is reduced significantly while retaining the production process's flexibility to changes. This means producing necessary products at the necessary time and decreasing the WIP (Work in process) inventory considerably (Ward & Zhou 2006). Moreover, according to Ohno (1988), using the JIT technique in manufacturing companies can decrease the inventory level to zero.

The requirements of producing the necessary parts at the needed time are a) reducing setup time, b) categorising technologies in the production process, c) Total Preventative Maintenance (TPM), d) Kanban system, e) multi-task staff, and f) regular quality control cycle.

Kanban

Kanban in Japanese means 'card' or 'visible'. Kanban are cards that have information regarding the number of products that need to be produced, and the origin and destination of the products. This tool was developed by Ohno (1988) to control the production activities between processing and implementation of JIT in the Toyota Motor Company. This tool allows inventory management and material flow in the manufacturing process to be simplified. It also helps to manage the maintenance of a small number of materials at the time of usage in the production line and to refill whenever a Kanban is created instead of loading more materials than needed (Hobbs 2004). This tool leads to a significant reduction of WIP materials, overproduction and inventory management cost, as well as improvement of inventory flow, demand responsiveness and supply chain management (Gross & McInnis 2003; Hobbs 2004).

Cellular manufacturing

Cellular manufacturing arranges the manufacturing process and production layout to efficiently facilitate the production flow. This rearrangement leads to reducing the time wasted on transportation of tools, workers, and materials and consequently reduces delays (Suzaki 1985).

This technique categorises machines or processes into groups based on the part or part families produced by them. The main purpose of this approach is to define part families which categorise the products into part cells and allocate each one to machine cells, hence reducing the movement of intercellular parts (Heragu 1994). In this regard, a survey of 70 manufacturing companies was conducted and the results show several benefits of cellular manufacturing techniques, which are reducing setup time, reducing WIP inventory, decreasing handling cost of materials, reducing labour costs and significant improvement in quality, material flow, and machine and space utilisation (Heragu 1994).

Production smoothing

According to Abdulmalek and Rajgopal (2007), the production smoothing technique is a process used to transform the manufacturing line constant within days. In this technique, small batches of many types of products are produced in a short period of time instead of producing a large number of the same products successively (McLachlin 1997). Producing the same product batches in a short period of time has several benefits for manufacturing companies. This technique results in having the exact required amount of every product ready as an output at the end of the production process. Hence, this leads to a significant reduction in the inventory level and inventory cost as well as checking and reworking of finished goods (Suzaki 1985).

Standard work

Standard work is the most efficient method of manufacturing products through a balanced and standard flow that adds value to the process. One of the main goals of lean manufacturing is to decrease variabilities in the production process. These variabilities are recognised in demand, manufacturing, and supplier. Manufacturing variabilities can increase the cycle time and lead to quality issues. According to Arnheiter and Maleyeff (2005), standardised work techniques (such as process mapping) can help a manufacturer to decrease any inconsistencies in the production process. This technique can help to perform the process with any variation in the output as well as improving the cost and quality.

Single Minute Exchange of Die (SMED)

This technique aims to reduce the setup process duration to less than ten minutes. It is an objective of this technique to transform the setup process to be done in a single-digit period of time. According to Agustin and Santiago (1996), there are two types of setup process in companies. The first one is an internal setup, which is done when the machine is in operation, and the second one is an external setup, which is done when the machine is off.

The aim of SMED is to identify the best arrangement of operations, prevent errors, remove unneeded phases and organise the workplace to simplify the setup process and transform the internal setup to an external one.

Visual control/ Visual management system

According to Hill (2011), this technique helps a manufacturer to create a system with indicators that can be seen easily. This tool helps supervisors to understand the status of the production line and monitor activities on the shop floor as well as find tools and equipment easily and indicate safety lines. “Dashboards” have been developed and used to facilitate the transfer of information, information demonstration and to report the current status of the manufacturing line. This technique facilitates the information communication process, e.g. customers’ needs, production schedules, aims and objectives throughout the company (Parry & Turner 2006). Key performance indicators are one example of visual control tools.

Safety improvement programs

Occupational Safety and Health Administrative (OSHA) regulations are set to be followed by most companies. Nevertheless, rather than just reporting work-related injuries and issues, if a continuous improvement approach to safety is taken, this program would be practical. For instance, manufacturers can submit the safety improvement programs by taking an improvement approach, which forces the company to implement the program's suggestions.

Information management systems

The aim of this technique is to simplify and facilitate the flow of information in the production line. An example of this information is data of product quality and operators, status data of the process, data of materials and availability of tools. This technique helps to reduce the waiting time to obtain data from the manufacturing process and any kind of errors due to the communication associated with production and its support.

Total Productive Maintenance (TPM)

According to Dennis and Shook (2007), Total Productive Maintenance was developed to enhance the efficient use of equipment during the production process without any interruption. This method is used to conduct regular maintenance cycles for the entire life of the equipment to increase overall equipment efficiency by frequent inspection with regular maintenance activities involving all employees with positions higher than the shop floor staff (Smith & Hawkins 2004). This method can reduce defects, safety issues and breakdown of the equipment (Ahuja 2011).

TPM can also integrate the productive and preventive specifications with innovative management strategies (Singh et al. 2006). All the employees should give appropriate attention to the equipment and inspect and maintain them regularly, as one of the major aspects of TPM is the employees' involvement from top managers to daily staff. The benefits of this tool are failure time reduction and an increase in machine and equipment availability, productivity, quality and safety (Smith & Hawkins 2004).

Total Quality Management (TQM)

Total Quality Management (TQM) is the process of continuous improvement in the manufacturing line to improve the quality of products by collecting feedback from employees (Terziovski & Samson 1999; Bayazit & Karpak 2007). According to Harris (1995), this technique has four main concepts. The first one is customer satisfaction, which identifies the organisation's customers both inside and outside of the organisation and regularly evaluates their satisfaction. The second one is the continuous improvement of the production system by using a quality improvement team to produce higher quality products and create a reward system for the employees' achievements. Total quality control is another concept of TQM, which removes the quality inspecting process as well as inspectors. The quality is measured by workers (for example, providing feedback) and statistical quality control is established at every stage of the manufacturing process. Finally, the last concept is training, which means providing training programs for all employees involved in the production process from the top managers to the shop floor staff.

2.3 Advantages of applying lean production system

It has been suggested that lean manufacturing aims to eliminate waste in every section of the organisation such as company management, product development, and customer and supplier relations to deliver the products/services to the customer efficiently. The aim of this production system is to utilise less of every resource such as labour efforts, inventory, time and space in different activities of the company, to deliver a high-quality product in the most economical and efficient manner.

In this manufacturing philosophy, wastes are defined as a sets of activities that add no value to the production process. Therefore, the aim of lean manufacturing is to utilise various tools and techniques to eliminate different kinds of waste in the production process. Thus, the benefits of lean manufacturing are to decrease manufacturing wastes in the organisation and improve productivity (Fullerton et al. 2003). Therefore, implementing lean strategies helps manufacturing companies become leaner across all departments. However, it is important to select a proper set of lean strategies to address the selected manufacturing wastes.

In addition, reduced wastes, improved customer value, integrated supply chain and value-adding organisation are some common characteristics of manufacturing companies which have applied the lean concept (Smith & Hawkins 2004). According to Shah and Ward (2003), lean manufacturing can reduce the inventory level and manufacturing time by 50 percent. Also, the lean implementation does not require huge investment in Information Technology (IT) sector. Therefore, a lean production system has several effects on the organisation, such as improvement in the production process, customer satisfaction, labour productivity and quality, manufacturing lead time, cycle time and cost reduction (Shah & Ward 2003; Bhasin & Burcher 2006).

In research conducted by Vinodh and Chintha (2010), four major benefits of lean manufacturing are described (Vinodh & Chintha 2010):

- Reduced buffering cost
- Increased product flexibility
- Reduced processing duration
- Increased delivery speed

Lean manufacturing transforms the production process to a clear, consistent and chronological flow process in all areas. These benefits have encouraged many manufacturing companies to apply lean strategies and tools for more than two decades to achieve a competitive advantage (Behrouzi & Wong 2011).

The aim of the manufacturing process is the transformation of the raw materials to the final product. The whole process consists of three different kinds of activities to make this transformation possible (Abdulmalek & Rajgopal 2007): Value-adding activities (VA), Unnecessary non-value-adding activities (NVA), and Necessary but non-value adding activities (NNVA). According to Womack and Jones (2003), value-adding activities directly lead to the value of the final products and are essential because they result in the improved quality of the final products and have significant impacts on the customers' satisfaction. Also, these activities are essential and cannot be removed in future operation models. Unnecessary non-value adding activities (NVA) are also known as pure wastes because they deliver no value to the final products. It is essential to eliminate these activities immediately without any detriment to the manufacturing process (Womack & Jones 2003). Necessary but non-value adding activities (NNVA) are necessary but create no value for the final products, mainly due to technological and financial limitations. Womack and Jones (2003) named these activities as type one Muda (a Japanese term meaning ‘futility, uselessness, wastefulness’). An example of this activity is paperwork between different departments in the organisation. However, the elimination of these kinds of activities requires investment and amendments in the production process. In addition, Ohno (1988) identified seven type of wastes, which are described in Table 2.1.

2.4 Overview of previous methodologies for selecting lean initiatives

Ayag (2005) and Leng et al. (2014) used Multi-criteria group-based decision making (MCGDM) for the problem of selection of lean management tools. For the MCGDM, the above mentioned authors used the Analytical Hierarchy Process (AHP) method to evaluate the concept designs and to select those with higher scores. Furthermore, they integrated this technique with the simulation generator to perform an economic analysis for the AHP selected concept designs (Wan & Chen 2009). This method is significantly influenced by preferences and involves numerous decision-makers and reference standards. Similarly, other research studies conducted by Vinodh et al. (2011), Ayağ (2007) and Anvari, Zulkifli, et al. (2014) , also used the AHP to select appropriate lean initiatives. Despite the considerable achievement of AHP, it has been argued that this method uses the same evaluation system to evaluate different alternatives (Singh et al. 2006; Amin 2012).

Table 2.1: Seven kinds of waste identified by Ohno (1988)

Wastes	Description
Overproduction	Producing more than actual demand. A common waste, which is mainly due to poor production planning and will result in extraneous transportation, the excessive level of inventory and capital investment, extreme production errors and lower labour productivity.
Waiting time	This refers to the idle status of materials, labour, and machines. This waste happens when labours, machines and materials wait to conduct the value-added process and will result in losing capital and productivity and also increasing manufacturing lead time.
Transportation	A material movement that does not contribute toward the final product. The ultimate goal of lean transformation is to minimise the cost of transportation within the organisation.
Processing	Excessive processing that does not add value to the final product. This kind of waste is related to the lack of proper process design or incorrect quality requirements.
On hand inventory	Consists of raw materials, work in process and finished goods that is sitting idle. These resources required investment but create no value to the final product. The aim of lean processing is to deliver the product within the shortest lead time, without any waste. However, holding enough inventory to decrease the lead time does not add value.
Movement	Excessive motion of material, machines, and labours without adding any value to the final products or services. These movements lead to low productivity, operator/material idle time, low product quality and manufacturing lead time.
Defects	Defective products are the results of poor process efficiency, process knowledge, and communication and low employee involvement.

In a method proposed by Hines and Rich (1997), a methodology for selecting value stream mapping (VSM) tools based on the relationships between VSM tools and production problems were proposed. In this method, the correlation matrix for VSM tools and manufacturing wastes was developed based on managers' opinions and review of the literature (Anand & Kodali 2008). Prior to this stage, the management team are trained to recognise the manufacturing wastes. Then, the relevant managers were asked to prioritise the identified wastes in their organisation based on their relative importance. Afterward, Hines and Rich (1997) established the interrelationship matrix for VSM tools and manufacturing wastes using previous literature and the managers' experience. However, their method lacks the analytical approach in selecting the best lean tools, and is also limited to the set of VSM tools and other lean strategies were ignored.

In another research study conducted by Lemieux et al. (2013), an operational approach was developed to assist managers and decision-makers in identifying lean and agile improvement tools according to the objectives of the performance. This framework includes a maturity-based casual/relations matrix. This matrix interrelates production process targets to improvement enablers according to the existing level of leagile (lean and agile) maturity of the enterprise. The framework developed in this research, identified and prioritised potential improvement initiatives for the selection problems (Lemieux et al. 2013). However, the proposed approach is not able to concentrate on one performance target at a time. Also, this method is mainly based on decision-makers' judgments and is restricted to a qualitatively assessment of the best improvement initiatives.

Yang et al. (2009) proposed the VIKOR[1] method by improving MCGDM (Multi-Criteria Group-based Decision-Making) and applying it to evaluate the risk of information security. Later, Chang (2010) and Anvari, Zulkifli, et al. (2014) improved the VIKOR method and arrived at the conclusion that differs group-based decision matrix for different alternatives and different norms. However, their method lacks the sensitivity of the evaluation criteria. In another method developed by Jing and Chang (2015), the original VIKOR method and the improved VIKOR method were applied to select appropriate lean tools for a yogurt production line in a dairy manufacturing company. This method prioritises selections based on different evaluation criteria corresponding to different criteria. Also, in another method, the fuzzy VIKOR method was developed for the supplier selection problems (Shemshadi et al. 2011). However, these models lack the coefficient sensitivity of the decision-making mechanism and assessment criteria that affect the decision results. the coefficient sensitivity of the decision-making mechanism is the sensitivity analysis of the change of the decision-making mechanism coefficient (r). For this purpose, they allowed for change in interval range [0, 1] of the decision-making mechanism coefficient r (the weight of the utility group) (Jing & Chang 2015).

Hu et al. (2008) developed a methodology with multiple objectives for selecting a project portfolio in manufacturing organisations. Although their methodology helps to implement lean strategies

[1] VIKOR Method is a multi-criteria decision making (MCDM) or multi-criteria decision analysis method. The name VIKOR appeared in 1990 from Serbian: VIseKriterijumska Optimizacija I Kompromisno Resenje. That means: Multicriteria Optimisation and compromise solution.

and the six sigma concept[2] effectively, they did not propose a methodology that suggests the proper set of lean strategies according to their impacts on wastes and performance measures. This will help them to get the benefits of implementing appropriate lean strategies to improve the manufacturing process. However, they do consider the financial benefits of selecting the project portfolio in lean and six sigma transformation and application in the manufacturing companies (Hu et al. 2008). In 1995, the Just-In-Time (JIT) quality matrix with the purpose of demonstrating the application and effectiveness of JIT tools was developed by Prasad. The matrix aims to select the best JIT tools for 11 scenarios by considering the JIT tools based on their impact on performance metrics and manufacturing wastes (Prasad 1995). However, in this method, only JIT tools were taken into consideration and other lean tools were overlooked. Also, their selection processes were limited to 11 scenarios and their method did not consider the resource limitation of the manufacturer in selecting the best solutions (Anvari et al. 2011).

Singh et al. (2006) improved the above methodology by using multi-attribute utility theory to integrate managers' opinions of all organisational sections. In this method, appropriate VSM tools are selected for a specific section of the production process using the prioritised information obtained from managers and the Analytical Hierarchical Process (AHP) (Singh et al. 2006). The results of this research illustrated that not all VSM tools were required to identify the production wastes. However, similar to the previous research, other lean tools that might be suitable were ignored, and the only focus was on VSM tools.

Herron and Braiden (2006) developed a methodology to understand the adaptability among the selected lean tools and for the problems of the company according to the relationships between the process stage and performance metrics; manufacturing wastes and metrics; and wastes and lean tools. The result of this study found that only a certain area of the production process was influenced by each lean technique (Amin 2012). However, they did not implement the suggested

[2] Six sigma is a quality control system developed in 1986 by Motorola, which emphasised cycle-time improvement and manufacturing defects reduction to less than 3.4 per million. Quality, defects, process capability, variation, stable operations and design for six sigmas are fundamental to this process.

lean tools to evaluate and analyse the effectiveness of lean tools in the improved manufacturing sections.

Furthermore, in research conducted by Inanjai and Farris (2009), a decision support tool for selecting lean tools based on the organisation requirements and their manufacturing wastes was developed. In this research, the authors developed a primary guideline on establishing the relationships between performance metrics, manufacturing wastes, and lean tools for future research work. In order to map the relationships between lean tools and manufacturing wastes, they used a four-point rating scale: 9 for high, 3 for medium, 1 for low and 0 for no correlation (Prasad 1995; Anand & Kodali 2008; Inanjai & Farris 2009). Amin (2012), used the same 4-point scale method, however, instead of 9, 3 was assigned for high correlation, and 2 was assigned for medium correlation. 1 was used for low correlation and 0 for no correlation, which was similar to the other scholars.

Amin and Karim (2013) proposed a systematic model to find the optimum solution for waste elimination. In their research, the correlation matrix was developed to establish relationships between lean strategies and manufacturing wastes. The manufacturing wastes were prioritised using managers' opinions. They then used a mathematical model to select a set of lean tools that have the highest impact on the critical manufacturing wastes. In this method, the cost and time constraints of the companies were also taken into account in the lean strategy selection method (Amin & Karim 2013). However, only the interrelationship between different lean tools and manufacturing wastes was considered in their method and the correlation between lean tools, performance metrics, and production wastes was not established to achieve the more accurate result from the methodology. In this regard, considering the impacts of lean strategies on performance metrics along with wastes can suggest lean tools for implementation to improve the performance based on competitive strategies as well as eliminating production wastes. Therefore, further extension of the developed model by Amin (2012) can assist manufacturers significantly by providing them with more accurate results.

2.5 Overview of tools for measuring leanness level

Many organisations focus on the implementation of lean strategies without comparing the leanness level of the organisation before and after lean tool implementation, thus being unable to recognise the measurable performance enhancement. This leads to the failure of many of these companies to implement lean production systems successfully and achieve the potential benefits of lean strategies. This is mainly due to a lack of knowledge and tools to measure, assess and compare the leanness level before and after the implementation of lean strategies (Soriano-Meier & Forrester 2002; Behrouzi & Wong 2011; Bhasin 2011).

Therefore, to track the improvement achieved by lean strategies, various tools and techniques were developed to measure the lean performance level (Tapping & Shuker 2003). In this regard, it is believed that leanness evaluation methodologies can be grouped into four major categories: value stream mapping (VSM), benchmarking, quantitative and qualitative lean evaluation methods (Wan & Chen 2008).

Several research studies have been focused on value stream mapping tools to measure the performance of the manufacturing process. Singh et al. (2006) defined value stream mapping (VSM) as a group of activities to deliver the final products and/or services to the customer. According to Womack and Jones (2003), VSM tools were developed to continuously simplify the production process. Seven VSM tools were developed for identifying the seven types of wastes defined by Ohno (1988) within the manufacturing process and its sources, improvement opportunities, and the leanness level of the organization by simplifying the production process (Hines & Rich 1997; Wan & Chen 2008).

Rother and Shook (1998) used these tools by focusing on time-based factors to evaluate the current and future leanness level of the organisation. These tools are very effective in identifying and illustrating the status of the organisation’s system and process arrangement. However, VSM tools have several weaknesses, such as a lack of ability to assess the leanness level quantitatively, and a weak ability to measure the qualitative performance indicators, such as customer satisfaction and labour productivity (Wan & Chen 2008; Amin 2012).

Another method that has been used in many research studies to measure the effectiveness and leanness of the performance is benchmarking (Rother & Shook 1998; Yasin et al. 2004; Chapman 2005; Bhasin & Burcher 2006). This method is used to illustrate an expressive value of the leanness level by defining lean metrics that comprise the critical lean principles. However, not all performance metrics are compatible with every manufacturing process (Wan & Chen 2008). Therefore, several researchers attempted to present a quantitative measure of the leanness level of the organisation using the benchmarking method (Kojima & Kaplinsky 2004; Gurumurthy & Kodali 2009; Singh et al. 2010). For instance, Azevedo et al. (2012) proposed an index to measure the leanness and agility, called the Agilean index, of manufacturing companies and correlate it with a supply chain. The Delphi techniques used in this research developed a set of weighted lean and agile measures for the supply chain as well as the importance paradigms through experts in the automotive industry. This research used these measures as a benchmark to compare the leanness and agility of the performance with other partners in the industry (Azevedo et al. 2012). In another research study conducted by Wan and Chen (2008), the leanness and agility level were quantified using Data Envelopment Analysis (DEA) and benchmarked against an ideal leanness boundary. In their method, they attempted to weight the performance indicators based on their relative importance (based on decision makers' judgment and surveys), which reflected the company's strategy and needs (Wan & Chen 2008). However, in these studies, only performance metrics related to time were considered and the manufacturing wastes were ignored. It can also be argued that the DEA score overestimated the leanness level by assuming the benchmarked practice to be 100% efficient.

Despite the advantages of the benchmarking method, it may reduce the accuracy of the leanness measurement due to the difficulty in finding the best performance in a relevant industry and availability of its performance data. In addition, every manufacturing system has its unique features in each section (such as cultural, social, economic and environmental factors), hence it is not practical to compare one against another (Wong et al. 2012).

Other research studies attempt to evaluate the leanness level of organisations qualitatively. According to Jordan and Michel (2001), assessing the leanness level of the organisation qualitatively is more effective and useful for manufacturer through lean implementation compared to the previous methods. Using surveys can help manufacturers to understand the level of lean strategy adoption in their organisation (Wan & Chen 2008). Wan and Chen (2009) developed a dynamic leanness measurement method with different templates of lean metrics that can be used in the different situations (Wan & Chen 2009). However, a specific set of metrics cannot be used in every system effectively, which may result in an inaccurate leanness score. Moreover, in this method, a large number of lean metrics templates need to be designed to be adaptive in various environments. In another method developed by Sopelana et al. (2012), the 'SMART maturity assessment' tool was proposed to measure the leanness index qualitatively in product development problems (Sopelana et al. 2012). In addition, Machado Guimarães and Crespo de Carvalho (2014) proposed a leanness measurement framework to evaluate the leanness score qualitatively for healthcare organisations. In another research conducted by Sekar et al. (2015) the leanness assessment framework was developed to determine the leanness index using fuzzy methods and benchmarking techniques in Indian pump manufacturing companies. These methods lack a crisp evaluation strategy and are time-consuming in implementation and understanding.

In addition, Florent and Zhen (2010) carried out a research study to develops an application and theories in supply chain management and proposed a leanness measurement approach for lean supply chain (Florent & Zhen 2010). Sánchez and Pérez (2001) recognised thirty-six different performance metrics based on a balanced scorecard and categorised them into six groups to measure the fluctuations through lean implementation. Moreover, Goodson (2002) used a rapid plant assessment (RPA) tool to assist experts in assessing if a company is lean in less than 30 minutes. This method consists of two tools: the RPA rating sheet and the RPA questionnaire. The results can have an impact on the decision-making process in benchmarking, continuous improvement, competitor analysis and achievements (Goodson 2002). In addition, Shah and Ward (2007) developed an operational assessment method to evaluate the degree of leanness. They selected ten production indicators in lean manufacturing from forty-eight different lean tools and practices based on their relative importance in the lean manufacturing systems (Shah & Ward 2007).

Moreover, Soriano-Meier and Forrester (2002) used the Karlsson and Ahlstrom model to conduct a survey by using two questionnaires with thirty companies in the ceramics industry in the United

Kingdom. In their survey, the emphasis of their nine groups of performance indicators was on the technical aspect of lean practices such as continuous improvement, pulling raw inventories, waste reduction, defects elimination, on-time deliveries, team multifunction, functions combination and vertical information system (Karlsson & Åhlström 1996; Soriano-Meier & Forrester 2002). In another study, the leanness score of the Chinese Hi-Tech industry was evaluated in nine areas based on a qualitative approach to examine the difference between the current level of leanness and its optimum level in this industry (Taj 2005, 2008; Taj & Morosan 2011).

To measure the leanness level of an organisation more accurately, quantitative methods have been developed using lean performance metrics (Nightingalea & Mizeb 2002). In a research study conducted by Zhan et al. (2018), empirical studies were carried out from 172 companies on green and lean practice in several Chinese manufacturing organisations to highlight the impacts of these practices on the production performance. Also, Rehman et al. (2018) developed a multi-criteria lean performance score (MCLPS) to measure the leanness score of Saudi Arabian enterprises. The developed methods in these research was based on a simple number, and managers' and decision-makers' opinion to analyse the effectiveness of the adopted manufacturing strategies and identify future improvement opportunities. In Detty and Yingling (2000), the benefits of lean strategies implementation were quantified using simulation-based methods in an assembly line. In addition, in other research studies, quantitative analysis frameworks and simulation approaches were developed to recognise four performance metrics, which are Overall Equipment Efficiency (OEE), First Time Through (FTT), Dock-to-Dock (DtD), and Build to Schedule (BTS) ratio, and to assess the efficiency of lean metrics in manufacturing organisations (Khadem et al. 2008; Gopinath & Freiheit 2012).

Moreover, a conceptual method was developed by Afonso and Cabrita (2015) for evaluating lean supply chain through the integration of financial and non-financial metrics. The developed framework helps manufacturers to identify the best set of lean performance metrics. Also, the proposed framework in this research study categorised leanness assessment into three main approaches, which are the evaluation of the lean implementation degree, measurement of the ultimate results obtained from lean implementation and finally, a combination of the first two approaches (Afonso & Cabrita 2015).

Furthermore, Elnadi and Shehab (2014) developed a conceptual methodology to measure the degree of leanness for product/service enterprises. They applied the proposed methodology in several UK manufacturing firms. In other leanness measurement methods, the performance metrics are categorised into different groups based on their specific nature. For instance, Allen et al. (2001) categorised performance metrics into four major groups: productivity, quality, cost, and safety. Ramesh and Kodali (2012) defined twenty-nine different manufacturing performance metrics through a literature review and divided them into quantitative and qualitative metrics. They used these metrics to develop a method for maximizing lean manufacturing performance in a company (Ramesh & Kodali 2012). However, this approach focused on individual performance metrics and did not integrate their leanness level to measure the overall leanness level of the organisation because the individual metrics cannot reflect the leanness level of the entire organisation (Wan & Chen 2008; Wong et al. 2012).

In a research study conducted by Levinson and Rerick (2002), manufacturing cycle efficiency (MCE) was used to measure the efficiency of the manufacturing process by comparing the duration of value-adding activities with the total manufacturing time (Levinson & Rerick 2002). This method illustrates the efficiency in different aspects of the manufacturing process, such as orders cycle time, average inventory level, system flow time, resource usage and labour productivity. However, Fogarty (1992) stated that this metric, which emphasises manufacturing efficiency is far from realistic. To address the weakness of the previous method, he introduced Value-Added Efficiency (VAE) (Fogarty 1992). However, both MCE and VAE are unable to calculate the overall leanness within the organisation because MCE and VAE only focus on time-based aspects of the production process and fail to consider other aspects such as productivity, quality, customer satisfaction, labour productivity, and cost.

In another research study, Leung and Lee (2004) defined two major features of manufacturing companies: “operation leanness” and “new-value creativeness”. The operational leanness reflects the performance competencies of the companies in using the input in a more effective and efficient manner by reducing the wastes in the production line. Moreover, Katayama and Bennett (1999) measured the level of the leanness of the companies by “Labour productivity.” However, this can lead to over-investment of the managers in automation and overlooking of other benefits of lean manufacturing. For instance, in the automotive industry, customer satisfaction factors (such as on-time delivery and quality) are more important in order to be successful in the market and the leanness assessment is based on their customers. However, these studies did not provide a quantitative measure of the leanness level of the companies and they failed to provide an index which reflects the overall leanness level.

In this regard, some research studies attempt to synthesise the metrics because each metric reflects a particular aspect of the organization concerned (Amin 2012; Wong et al. 2012). For instance, in Amin (2012), the overall leanness level of the manufacturing firm is measured using fuzzy-set theory. Amin selected both qualitative and quantitative performance metrics in his measurement method and developed a fuzzy-logic based leanness assessment model by synthesising the leanness level of each performance indicator into an overall leanness index (Amin 2012). However, in all of these measurement methods, the interrelationships between performance indicators were not taken into consideration: a variation in one metric may lead to changes in others (Wan & Chen 2008; Wong et al. 2012).

Furthermore, one approach can be used to assign priority weights to performance metrics. Wong et al. (2012) and Anand and Kodali (2008) used an analytic hierarchy process (AHP) and analytic network process (ANP) to assign relevant weights to cost, on-time delivery and quality performance determinants (Anand & Kodali 2008; Wong et al. 2012). This method was developed by Saaty (2004) to provide a pairwise comparison matrix to calculate the priorities of a set of lean performance metrics. Agarwal et al. (2006) used the same method to assign weightings to performance metrics in assessing the lean, agile and leagile (hybrid of lean and agile[3]) level of an organisation (Agarwal et al. 2006). However, this method is used when the level of uncertainty is near zero and reliable information is sourced.

[3] Agile manufacturing is an approach to responding to the dynamic demands of customers while sustaining the quality standards and controlling the overall manufacturing costs.

2.6 Measuring the leanness using fuzzy set theory

Researchers have attempted to introduce fuzzy logic into the leanness measurement approach because it is believed that leanness and lean measurement cannot be predicted with certainty. The judgment can be different for describing the leanness level of each performance metric and can be explained with different grades such as lean, leaner or leanest[4]. Therefore fuzzy logic is used to deal with ambiguities in this area (Lin et al. 2006; Bayou & Korvin 2008; Vinodh & Chintha 2010; Balaji & Vinodh 2011; Behrouzi & Wong 2011).

In this regard, one example of the fuzzy logic application in leanness assessment method is a research study conducted by Balaji and Vinodh (2011). They introduced a fuzzy-based leanness assessment model by using linguistic terms to evaluate performance metrics and their relative importance in terms of weighting. They defined fuzzy numbers for each linguistic value and measure using a fuzzy performance index (FPI) based on the defined numbers. They indicated that leanness level is a vague phrase which can be measured and expressed by fuzzy set logic (Balaji & Vinodh 2011). Furthermore, Vimal and Vinodh (2012) assessed the leanness level of an organisation by using IF-THEN rules. They defined five enablers, thirty lean criteria and fifty-nine attributes to cover various aspects to measure the leanness score (Vimal & Vinodh 2012). In this method, the linguistic variables are employed based on experts' opinions to rank the performance indicators and convert these linguistic terms to fuzzy numbers. In another research study conducted by Vinodh and Chintha (2010), they developed a leanness assessment model by using a multi-grade fuzzy approach. In their model, they defined the leanness index that can be calculated by multiplying the overall assessment factor and overall weightings. They asked for managers' opinions on their leanness measurement model to determine assessment factors and weightings for each lean enabler (Vinodh & Chintha 2010). However, this weighting method does not explore the advanced methods of fuzzy logic to determine the performance ratings and allocate the relevant weightings for each metric. In addition, different managing teams might have different opinions and estimations regarding the leanness level of each metric and its weighting.

[4] Another example is the level of customer satisfaction that can be assessed by using different terms, such as high, very high or highest. These can be interpreted differently and the judgment might be varied for each person.

In a research conducted by Fullerton and Wempe (2009), the importance of financial and non-financial measures was focused on for assessing leanness index. They proposed four groups of hypotheses to carry out a survey on 121 US manufacturing firms. In the first hypothesis, the relationship between shop-floor staff associated with reducing setup time, implementing cellular manufacturing and improving production quality was examined. In the second hypothesis, the relationship between non-financial manufacturing performance and lean activities were assessed. In the third and fourth hypotheses, the relationship of lean initiatives with financial performance metrics and non-financial metrics were examined respectively (Fullerton & Wempe 2009).

Bayou and Korvin (2008) introduced a systematic approach to measure the leanness level of an organisation. They also used fuzzy set theory in their measurement method that has more compatibility with the uncertainties of the leanness assessment. They applied their method to compare the leanness level of the Ford and General Motors companies by using the Honda Motor Company as a benchmark. However, as mentioned previously, using the benchmarking approach is useful but finding the best practice in a particular area is difficult. Furthermore, they only considered financial performance indicators in their assessment model and they did not assume interrelationships between these metrics to measure the overall leanness. In another research study conducted by Behrouzi and Wong (2011), a fuzzy-based leanness assessment model was developed by using four performance categories and two performance metrics for each of the categories. However, their method lacks a proper weighting approach for the performance metrics, and the eight performance metrics are assumed to have the same weighting (Behrouzi & Wong 2011). These methods did not integrate the qualitative and quantitative methods to measure the overall leanness of the companies using the advanced fuzzy-logic function and present a single overall leanness level for the manufacturing firms.

In addition, in the method developed by Amin (2012), the fuzzy logic theory was used to convert the collected data of each performance metrics into the fuzzy number and quantify the leanness score of the company. Their proposed fuzzy-based model integrated different performance measures to calculate the integrated leanness index. The result from their method is a single unit-less number that reflects the overall leanness score for the defined scope of the project. Amin (2012), assumed that all performance measures are equally important and did not consider the interdependent relationships between performance metrics. However, performance metrics from different categories (such as cost, quality, productivity, and safety) may be taken equally important due to competitive strategies. Therefore, it is essential to develop a methodology that measures the overall leanness score of the production performance considering the interdependent relationship of performance metrics. It is essential to prioritise different performance metrics and develop a weighted leanness evaluation model.

2.7 Identified research gaps and conclusion

According to the literature review, previous studies have been focused on implementing lean techniques and their measurement approaches. It is essential to select and suggest the best set of lean tools for the company because misapplication of lean tools can increase manufacturing costs, time and wastes significantly. Therefore, several research studies attempted to propose a methodology to suggest the best set of lean techniques to improve production performance and eliminate the identified wastes (Prasad 1995; Anand & Kodali 2008; Amin 2012; Amin & Karim 2013). In these methods, the selected manufacturing wastes and performance metrics were ranked to use in a lean strategies selection method.

Currently, there are many lean strategies and techniques available, but it is critical that the most appropriate combination of lean tools is selected to maximise their effectiveness in eliminating waste. A methodology for selecting the best set of lean tools should be developed to prevent an increase of non-value-adding activities caused by incorrect selection. Thus, it is vital to suggest the best set of lean strategies with the highest impacts on critical performance metrics and manufacturing wastes. Several manufacturers choose lean strategies based on their judgment without any logical assessment of their subsequent effects. However, the current lean strategies selection methods explained in the literature lack an analytical and systematic approach to select proper lean strategies according to their impacts on manufacturing wastes and performance metrics. Some of these studies only focused on one type of lean tool, e.g. Just-In-Time or Value Stream Mapping, and did not consider a different set of lean strategies in their selection methods (Prasad 1995; Hines & Rich 1997; Singh et al. 2006). In addition, in some selection methods, either the interrelationship between lean tools and manufacturing wastes or lean tools and performance metrics were established. They consider these interrelationships to choose lean tools that affect the most critical performance metrics and manufacturing wastes (Herron & Braiden 2006; Inanjai & Farris 2009; Amin & Karim 2013). These methods lack a comprehensive consideration of interrelationships between lean tools, production problems, and performance metrics for selecting the best lean tools that may lead to the most significant impacts on the critical performance metrics and wastes.

Accordingly, the development of a methodology to select the most effective lean tools based on the interrelationships between different lean strategies, performance metrics and manufacturing wastes is essential. In this respect, this research aims to develop a methodology to suggest the best set of lean techniques based on their relationship with performance metrics and manufacturing wastes. This research will attempt to establish an interrelationship between lean tools, manufacturing wastes and performance metrics at the same time to suggest the best lean tools to answer Question 1 (How can one select the most appropriate lean strategies based on the interrelationships between different lean tools, performance metrics, and manufacturing wastes?). The result from the proposed methodology in this research will provide a more accurate sequence of lean techniques for implementation which results in optimising the improvement of performance metrics and reduction in manufacturing wastes.

Nowadays, many researchers understand the significance of the numerical measurement of organisation leanness index to compare and track the leanness value of the organisation for the existing performance and after implementing lean tools. Moreover, it can be understood from the literature that different leanness assessment approaches were used in different studies. These methods employed various performance metrics in the assessment method. However, the current literature does not provide a systematic approach that considers the interrelationships between lean performance metrics. Because each performance metric has a different behaviour, variation in one metric might have an effect on other metrics. However, current literature lacks a valid methodology that measures the overall leanness of the organisation considering the interrelationships between lean performance metrics from different groups. These methods consider all performance metrics to be equally important during their analysis. Although these methods can be useful in some situations, none of them offers a comprehensive method that synthesises both quantitative and qualitative metrics based on their interrelationships due to different competitive strategies. For instance, a reduction in manufacturing costs can lead to a reduction in the product's quality, and enhancing labour productivity can reduce the manufacturing time. Also, decision makers and managers may desire to prioritise the performance indicators and allocate weightings based on their relative importance (Wong et al. 2012). Therefore, it is critical to predict and consider their influences and interrelationships in the leanness assessment model (Wong et al. 2012). Failure to consider the interaction of performance indicators may lead to the inaccurate calculation of the overall leanness score. When each performance metric is allocated its relevant weighting, the leanness score can be compatible with changing manufacturing strategies (Wan & Chen 2008).

This research will attempt to answer Question 2 by developing a mathematical methodology using fuzzy set theory to allocate weightings to each performance metric and measure the leanness score of the organisation more accurately (Question 2: how can one develop a weighted fuzzy-based leanness assessment model by considering the interrelationships between performance metrics?). Consideration of these interrelated impacts and the relative importance of performance metrics in leanness measurement methodologies can assist manufacturers to achieve more accurate leanness index (Wong et al. 2012). In addition, assigning weightings for lean performance metrics can reflect an organisation's requirements more accurately (Wan & Chen 2008).

Finally, the aim of this research is to develop a weighted leanness measurement methodology that provides a more accurate overall leanness index of the production process by considering the interdependent relationship between lean performance metrics. The result from the proposed methodology will provide a more accurate score by prioritising performance metrics based on manufactures needs.

Chapter 3: Development of a methodology for selecting the best set of lean tools and relevant research methodology

Several lean tools and techniques have been developed with the aim of manufacturing waste elimination (non-value-adding activities) in an organisation. These tools help manufacturers to achieve competitive advantages. Chapter 2 explained some examples of lean manufacturing techniques such as JIT, TQM, TPM, cellular manufacturing and 5S as well as manufacturing wastes such as defects, unnecessary movements, setup time and overproduction. However, it is essential to implement appropriate lean tools to reduce critical manufacturing wastes and enhance the productivity of the company. As mentioned previously, inappropriate implementation of lean strategies can increase manufacturing cost and time and decrease efficiency in the production process. Also, it is vital to implement appropriate lean tools that target the critical manufacturing wastes and performance metrics to achieve the highest potential of lean manufacturing and improve productivity and efficiency in the company. Hence, this research study aims to select a set of lean tools from the vast number available according to the manufacturer's needs based on their interrelationships with performance metrics and manufacturing wastes.

In this chapter, the impacts of lean implementation, development of a mathematical model and the methodology for finding the optimum solution are presented in sections 3.1,3.2 and 3.4 respectively. These methodologies are developed to select the proper sets of lean strategies that are suitable for the manufacturing companies. Finally, section 3.5 of this chapter presents a real-life case study that utilised the methodology for selecting the proper set of lean tools. This section also validates the proposed methodologies through their application in the case study and sensitivity analysis.

3.1 Theoretical background

Lean manufacturing developed several tools and techniques to reduce all kind of resources such as time, cost and materials in the production process and other activities in the organisation. However, it is important to consider the impacts of these tools on the performance metrics and the manufacturing wastes to avoid inefficiency increase caused by misapplication of these tools (Prasad 1995; Hines & Rich 1997; Amin & Karim 2013). Several researchers demonstrated that lean transformation requires a significant amount of effort, resources (such as cost and time), the involvement of all employees and introduction of new principles in the production line as well as the changes in the culture and structure of the organisation. Therefore, it is important to implement a proper decision-making method for selecting the set of lean tools, because lean manufacturing can involve extra budget and time for implementing lean techniques, investment in the production and assembly line, alteration in management and maintenance strategies and increased risk to quality (Papadopoulou & Özbayrak 2005; Browning & Heath 2009; Wan & Chen 2009). Lean manufacturing, like any other new productivity program, should be selected properly, otherwise, it can disrupt the production process and impair productivity in the manufacturing organisations (Gautam & Singh 2008).

In this research, the aim is to reach the maximum level of perceived value during the lean transformation journey considering the interrelationship between lean tools, manufacturing wastes, and performance metrics while minimising the expense and period of lean adoption. However, external factors are not considered for the purpose of this research. The primary focus of this research is on facilitating the decision-making process for a more efficient manufacturing process within the internal constraints such as development and investment budget and time. Therefore, the primary focus of this research study is to establish the more accurate interrelationships between different factors (lean tools, performance metrics, and manufacturing wastes) and facilitate the decision-making process considering internal factors such as investment time and cost constraints. This chapter aims to increase the perceived value of selecting lean strategies to its maximum level in the company based on the interrelationship between these tools, performance metrics and manufacturing wastes within time and budget constraints. The optimum solution will be the desired perceived value by manufacturers to accomplish the reduction or of elimination of wastes in their production line.

The next section presents the methodology developed to suggest the proper set of lean strategies (based on their relationships with lean performance metrics and manufacturing wastes) to maximise the perceived value of manufacturing wastes reduction. This methodology is also used for finding the optimised solution.

3.2 The research approach of development a methodology for suggesting the best set of lean tools

This section presents a brief description of each step to achieve the first research objective, selecting proper lean strategies for a manufacturing organisation considering the relationship between lean tools, performance metrics, and manufacturing wastes. To achieve this the following steps should be fulfilled:

- Methodology development for finding the best set of lean strategies

This research will develop the relationship matrix between lean tools, performance metrics, and manufacturing wastes to suggest the best set of lean strategies. This matrix will illustrate the impacts of each lean strategy on selected performance metrics and manufacturing wastes. The manufacturing wastes were defined from production problems existing in the organisation and the set of lean tools and performance metrics (both qualitative and quantitative) were identified based on the specifications and requirements of the organisation's industry. The identified manufacturing wastes and performance metrics will be prioritised based on the manufacturers' requirements. Therefore, the mathematical methodology will use this matrix to select and suggest the proper set of lean tools to achieve the highest perceived value and have the highest impacts on the critical performance metrics and reduction in manufacturing wastes. The details of the developed model are provided in this chapter.

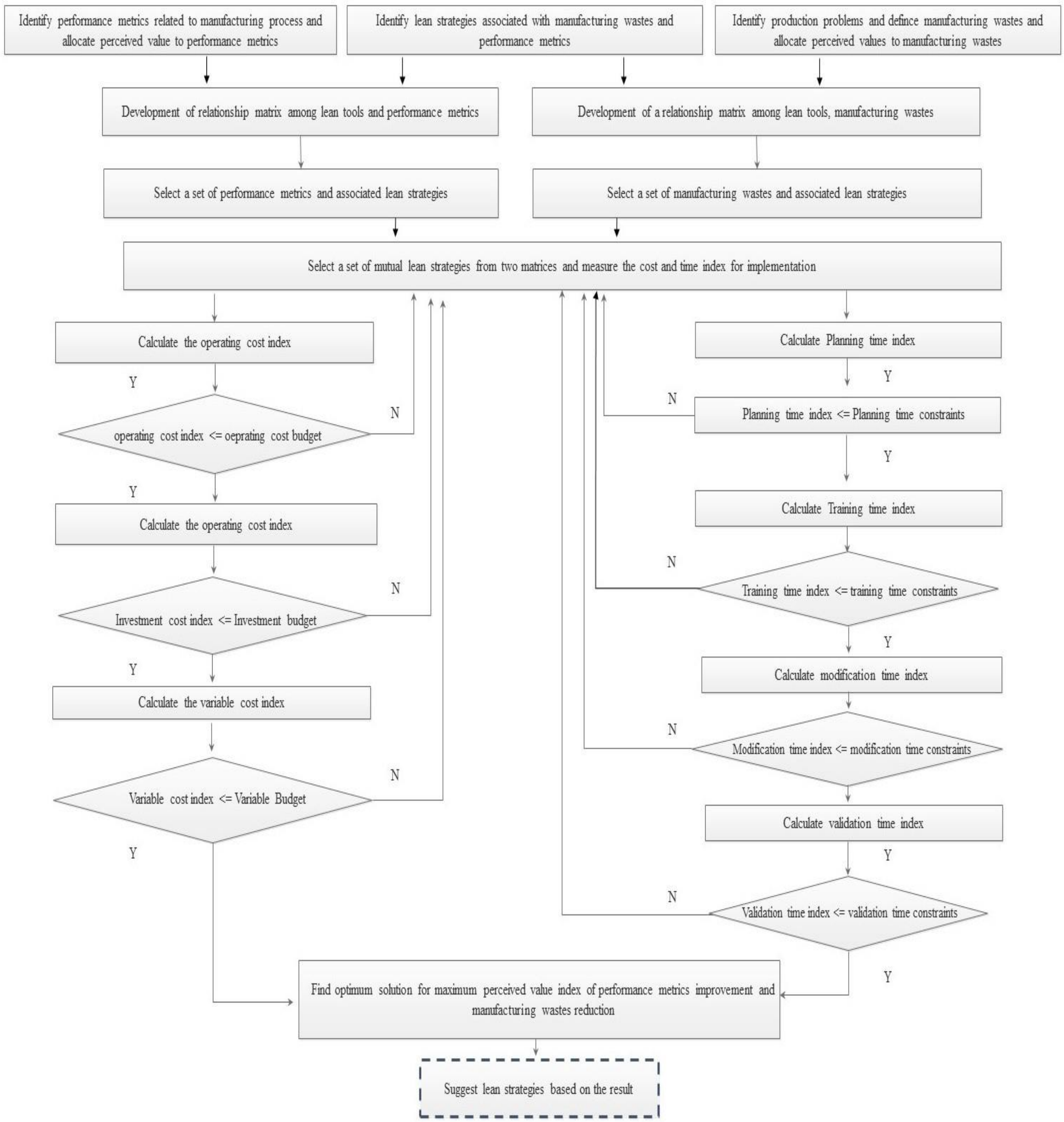

Figure 3.1: A structure of the proposed model for selecting lean strategies for the performance metrics and manufacturing wastes.

In the next stage, an approach for finding the proper set of lean tools for identified manufacturing wastes and performance metrics was developed. Setup time, excess motion and transportation, defects, improper process, and finished goods inventory are identified manufacturing wastes for the purpose of this research (Hines & Rich 1997; Amin 2012). The most commonly used lean strategies have been selected based on the preference of the decision makers and requirements and industry of the organisation. Moreover, lean strategies included in this research are: 5S, JIT, Kanban, Total Quality Management (TQM), Total Production Maintenance (TPM), Single Minute Exchange of Die (SMED), Cellular Manufacturing, Standard Work Process, Visual Management System, Safety Improvement Program, Information Management System and Production Smoothing (Abdullah 2003; Abdulmalek & Rajgopal 2007; Amin 2012). In this step, an interrelationship matrix has been developed to establish interrelationships between selected lean tools, wastes and performance metrics. The proposed methodology presents a step toward suggesting a proper set of lean initiatives based on the correlation matrix.

3.3 Developed methodology for selecting the best set of lean tools based on their impacts on performance metrics and manufacturing wastes

In this research study, the benefits of lean strategies implementation for reducing manufacturing wastes and improving performance metrics is assessed by developing the perceived value index, which is a unit-less value. The definition of perceived value is the perception of manufacturers of the value of reducing production wastes and enhancing performance metrics. Perception of manufacturers is evaluated by allocating the relative importance rates to their goal.

In this research, the manufacturers' perception of reducing wastes and improving performance metrics are converted into numerical priority values to their goals. The higher importance weights for manufacturing wastes or improving performance metrics can increase the perceived value index. Moreover, the project's cost and time associated with lean implementation are considered in this research study using approaches developed by Amin (2012). The cost index of the lean implementation consists of operating cost, variable, investment and risk cost. Time indexes are planning, training, modification and validation time of lean implementation. Finally, in this research study, the decision function has been developed by considering the relationships between lean tools, performance metrics, and manufacturing wastes to find the proposer set of lean strategies.

3.3.1 Perceived value of implementing lean manufacturing

The primary aim of lean strategies implementation is to eliminate or reduce manufacturing wastes as well as improve the level of performance metrics in the organisation. Therefore, this research study considers two steps to achieve the first objective of this research:

- Consider the relationship between lean tools and performance metrics.
- Maximise the perceived value of the lean implementation within the cost and time constraints.

In every innovation project, improvement activities should have a contribution toward the organisation's objectives; otherwise, it will be considered a non-value-adding activity, which should not be pursued further. In this regard, a set of lean tools should be identified to maximise the perceived value of reducing manufacturing wastes and improving performance metrics within the budget and time constraints.

Based on the mathematical model of Gautam and Singh (2008), the perceived value index increase of adopting n lean strategies can be measured by Equation 3.1:

$$perceived\ value\ index\ increase = \sum_{i=1}^{n} L_i\, P_{1i} \qquad \text{Equation 3.1}$$

L_i is a binary variable dependent on whether the i^{th} lean strategy is implemented, and the perceived value index increase due to adopting the i^{th} lean strategy is represented by P_{1i}. In this equation, L_i=1 if the i^{th} lean tool is selected and L_i =0 if the i^{th} lean strategy is not selected. Therefore, adopting of the i^{th} lean strategy leads to P_{1i} increase in the manufacturer's perceived value index.

Also, if two implemented lean strategies interact, extra change occurs in the perceived value index, which can be expressed by the following equation:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, P_{2ij} \qquad \text{Equation 3.2}$$

In this regard, the total perceived value index change of lean transformation is calculating by:

$$Total\ change\ in\ perceived\ value\ index = P_{0i} + \sum_{i=1}^{n} L_i \, P_{1i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, P_{2ij} \qquad \text{Equation 3.3}$$

In Equation 3.3, P_{0i} is the perceived value of no lean strategy implementation. It means the perceived value of implementing no lean tools could be a legitimate option, because there is always a cost associated with implementation. In this research study, P_{1i} is defined as obtained value of implementing the i^{th} lean strategy to address the two objectives, which are improving lean performance metrics and reducing manufacturing wastes that are determined by the decision-making team in the organisation.

However, in this research study, the effect of forced change is not considered in calculating the perceived value index. An example of the effect of forced change is in implementing JIT and TPM, which are two interrelated lean techniques. Therefore, implementation of these two lean strategies requires a balanced relationship during implementation. This means implementing two techniques at the same time without considering the positive and negative impact on each other can cause an increase in the implementation cost, time and quality risk.

3.3.2 Lean implementation resources

In this research study, it was assumed that implementing lean strategies brings leanness to the current process, reduces manufacturing wastes and improves performance metrics. Therefore, the costs of lean implementation considered in this research study are categorised into four groups as well as the time of implementing lean strategies (Gautam & Singh 2008; Amin & Karim 2013). Cost resources of lean implementation are operating cost, amortisation cost, variable cost and risk cost while time resources of lean implementation are planning, training, development and validation time. Therefore, the perceived value index of the lean implementation is maximised within the organisation's cost and time constraints using the proposed model (Amin, 2012).

3.3.2.1 Financial resources of lean implementation

The financial ability of manufacturing organisations should be considered when adopting and implementing lean strategies. Manufacturers are often reluctant to adopt lean initiatives like other improvement programs as it requires a significant amount of investment and funds for purchasing new equipment, training employees and consultation (Bachamada 1999; Gautam & Singh 2008; Mirzaei 2011). Therefore, it is essential to consider the financial resource constraints of the organisation when adopting lean strategies (Shah & Ward 2003; Amin & Karim 2011). The following table presented the financial resources of lean implementation and the relevant equations for measuring these resources (Gautam & Singh 2008; Amin 2012).

Cost index	Definition	Equation
Operating cost	The cost of operating lean tools refers to costs associated with utilities and equipment usage cost (e.g. cost of moving equipment from station to the warehouse), employee cost, power cost and maintenance and repair cost.	$C_{0_{0i}} + \sum_{i=1}^{n} L_i\, C_{O_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, C_{O_{2ij}}$ Equation 3.4
Amortisation cost	According to Eswaramoorthi et al. (2010), the amortisation cost of lean strategy implementation refers to the purchase cost of tools, equipment and other accessories required for the manufacturing line, which is essential for implementing lean strategies successfully (Bachamada 1999). These kinds of investment cost consider the time value of the money and reimbursement duration. Amortisation cost is related to the complexity of the investment for modifying the current manufacturing process as well as the lean application level.	$C_{A_{0i}} + \sum_{i=1}^{n} L_i\, C_{A_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, C_{A_{2ij}}$ Equation 3.5

Variable cost	Variable cost is directly related to the production volume, which increases when production process increases and reduces when it decreased. Raw materials inventory, packaging and costs associated with shop floor staff are some examples of variable costs. Therefore, to normalise this index, it is necessary to use the volume of the production when calculating the variable cost of a lean strategy implementation.	$C_{V_{0i}} + \sum_{i=1}^{n} L_i\, C_{V_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, C_{V_{2ij}}$ Equation 3.6
Risk cost	Risk cost is a consequence cost of any improvement and development programs that indirectly affect the total cost of the project. As manufacturing activities for improving performance metrics and reducing manufacturing wastes are being changed, lean implementation can bring risk towards productivity and efficiency of the production process. Risk caused by implementing lean strategies in the organisation can be translated by using the probability of failure due to lean implementation and risk cost. The probability of failure ($p(i)$) usually associated with the level of lean implementation and the current manufacturing system complication.	$C_{R_{0i}} + \sum_{i=1}^{n} p(i) L_i\, C_{R_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} p(i) L_i L_j\, C_{R_{2ij}}$ Equation 3.7

3.3.2.2 Time value indexes of lean implementation

The lean transition process is considered to be a time-consuming process by many manufacturers. This impression needs to be minimised to implement lean strategies successfully (Bachamada 1999; Papadopoulou & Özbayrak 2005; Amin & Karim 2013). According to Bachamada (1999), the lean implementation time can be categorised into several groups such as planning, validation, infrastructure development and training time. Several companies overlapped the timing of these stages with each other to shorten the lean implementation duration. The following table presented the time value index of lean implementation and the relevant equations for measuring these indexes (Gautam & Singh 2008; Amin 2012).

Time index	Definition	Equation
Planning time	Similar to every initiative and improvement program, lean implementation requires planning time by decision makers and the management team prior to application. During this stage, planning for development of facilities and requirements for implementation procedure is conducted. The preparation and design stage for adopting lean tools is the primary activity of the planning stage (Anvari et al. 2011). Preparation consists of gap assessment, wastes identification, objective establishment and forming an implementation team. The design stage consists of analysing the current state, mapping and planning implementation of the new project and identifying the performance metrics.	$T_{P_{0i}} + \sum_{i=1}^{n} L_i \, T_{P_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, T_{P_{2ij}}$ Equation 3.8
Training time	Selecting an appropriate set of lean tools requires extensive knowledge and experience regarding each lean strategy to achieve successful implementation of lean tools. Therefore, managers and decision makers should be aware of the commencement point and the procedures of the lean implementation project. Also, it is vital to obtain appropriate knowledge about lean initiatives because copying lean strategies from other companies may lead to failure in implementing lean principles. This is mainly due to the different requirements and specifications of the manufacturing firms (Allen et al. 2001; Wan & Chen 2009; Anvari et al. 2010). Therefore, the training time required for lean strategy implementation consists of the time of training about a particular lean tool and its impacts on manufacturing wastes and performance metrics, its implementation and maintenance procedure and operation.	$T_{T_{0i}} + \sum_{i=1}^{n} L_i \, T_{T_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, T_{T_{2ij}}$ Equation 3.9

Infrastructure development time	The infrastructure development time is defined as a period necessary to improve the present manufacturing performance to apply lean tools. This process requires a significant amount of effort, time and involvement of all employees from shop floor staff to top managers as well as transformation in the structure and culture of the organisation.	$T_{D_{0i}} + \sum_{i=1}^{n} L_i \, T_{D_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, T_{D_{2ij}}$ Equation 3.10
Validation time	Similar to any kind of improvement project, the lean implementation process may have risks associated with cost, materials and quality. Therefore, the validation stage is important to reduce such risks and cost (Miller et al. 2010). This process provides enough evidence that the new systems are effective and efficient and meet the requirement of the organisation. Also, it can determine the list of equipment, tools and systems that have an effect on the quality of the product as result of change in the existing system.	$T_{V_{0i}} + \sum_{i=1}^{n} L_i \, T_{V_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, T_{V_{2ij}}$ Equation 3.11

3.3.3 Function and constraints of the proposed methodologies

As mentioned earlier, the aim of this research is to develop a methodology that suggests lean tools that consider the impacts of lean strategies on both performance metrics and production wastes. Previously, the aim of lean strategies selection methodologies was to implementing lean tools that help manufacturers in reducing manufacturing wastes. However, this research developed a methodology that suggest lean tools with the purpose of improving performance metrics from different measures as well as eliminating manufacturing wastes. Therefore, the proposed method in this research helps manufacturers to implement lean strategies based on different competitive strategies while reducing wastes and optimising their performance. This objective can be translated in the following mathematical equation (Amin, 2012):

$$Maximum\left(\left(PW_{0_i}+\sum_{i=1}^{n}L_i\,PW_{1_i}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,PW_{2ij}\right)+\left(PM_{0_i}+\sum_{i=1}^{n}L_i\,PM_{1_i}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,PM_{2ij}\right)\right)\quad \text{Equation 3.12}$$

$$\begin{aligned}Minimize\ the\ total\ cost &=\left(\left(C_{O_{0i}}+\sum_{i=1}^{n}L_i\,C_{O_{1i}}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,C_{O_{2ij}}\right)\right.\\&+\left(C_{A_{0i}}+\sum_{i=1}^{n}L_i\,C_{A_{1i}}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,C_{A_{2ij}}\right)\\&+\left(C_{V_{0i}}+\sum_{i=1}^{n}L_i\,C_{V_{1i}}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,C_{V_{2ij}}\right)\\&\left.+\left(C_{R_{0i}}+\sum_{i=1}^{n}p(i)L_i\,C_{R_{1i}}+\sum_{i=1}^{n}\sum_{j=1}^{n}p(i)L_iL_j\,C_{R_{2ij}}\right)\right)\end{aligned}\quad \text{Equation 3.13}$$

$$\begin{aligned}Minimize\ the\ total\ time &=\left(\left(T_{P_{0i}}+\sum_{i=1}^{n}L_i\,T_{P_{1i}}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,T_{P_{2ij}}\right)\right.\\&+\left(T_{T_{0i}}+\sum_{i=1}^{n}L_i\,T_{T_{1i}}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,T_{T_{2ij}}\right)\\&+\left(T_{D_{0i}}+\sum_{i=1}^{n}L_i\,T_{D_{1i}}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,T_{D_{2ij}}\right)\\&\left.+\left(T_{V_{0i}}+\sum_{i=1}^{n}L_i\,T_{V_{1i}}+\sum_{i=1}^{n}\sum_{j=1}^{n}L_iL_j\,T_{V_{2ij}}\right)\right)\end{aligned}\quad \text{Equation 3.14}$$

In Equation 3.12, the aim is to maximise the perceived value index of lean strategies implementation for reducing wastes and improving performance metrics. Therefore, in this equation PW_{0_i} is the perceived value index of reducing wastes without lean strategy implementation, PW_{1_i} is the perceived value of reducing wastes due to adopting one lean strategy, and PW_{2ij} is the value of forced changes. Similarly, PM_{0_i} is the perceived value of improving performance metrics without lean implementation, PM_{1_i} presents the perceived value index of improving performance indicators due to adopting a lean tool and PM_{2ij} is the perceived value index of the effect of forced changes. Besides, for maximising perceived value of appropriate implementation of lean strategies, the total cost and time needs to be minimised using the following Equation 3.13 and Equation 3.14 (Amin, 2012).

In any development project, there are some resources and budgetary constraints for implementing a new initiative. These constraints are given by the top managers to the development team before starting a new project. The budget and time-based limitations that are defined in this research study are presented by the following equations:

$$C_{0_{0i}} + \sum_{i=1}^{n} L_i \, C_{O_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, C_{O_{2ij}} \leq Operating\ cost\ budget$$ Equation 3.15

$$C_{A_{0i}} + \sum_{i=1}^{n} L_i \, C_{A_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, C_{A_{2ij}} \leq Amortization\ cost\ budget$$ Equation 3.16

$$C_{V_{0i}} + \sum_{i=1}^{n} L_i \, C_{V_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, C_{V_{2ij}} \leq Variable\ cost\ budget$$ Equation 3.17

$$C_{R_{0i}} + \sum_{i=1}^{n} p(i) L_i \, C_{R_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} p(i) L_i L_j \, C_{R_{2ij}} \leq Risk\ cost\ budget$$ Equation 3.18

$$T_{P_{0i}} + \sum_{i=1}^{n} L_i \, T_{P_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, T_{P_{2ij}} \leq Planning\ time\ limit$$ Equation 3.19

$$T_{T_{0i}} + \sum_{i=1}^{n} L_i \, T_{T_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, T_{T_{2ij}} \leq Training\ time\ limit$$ Equation 3.20

$$T_{D_{0i}} + \sum_{i=1}^{n} L_i \, T_{D_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, T_{D_{2ij}} \leq Developement\ time\ limit$$ Equation 3.21

$$T_{V_{0i}} + \sum_{i=1}^{n} L_i \, T_{V_{1i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \, T_{V_{2ij}} \leq Validation\ time\ limit$$ Equation 3.22

In Equation 3.15 to Equation 3.22, the total cost budget and total time limit are given by a manufacturer for a lean implementation project. In the next section, the methodology for using the decision-making equations presented in this section is described.

3.4 Essential steps of the proposed methodology for suggesting lean tools

The previous section explained the proposed methodology for suggesting the best set of lean techniques. The steps of the proposed model and the detail of each step is described in this section:

3.4.1 Identifying performance metrics

Each performance metric is a variable that is measured qualitatively or quantitatively. These variables are used to express the efficiency and effectiveness of an operation (Neely & Platts 2005; Ramesh & Kodali 2012). In a research study conducted by Dennis and Shook (2007), there were six main lean performance metrics: cost, productivity, quality, delivery, safety, environment and morale. Conventionally, researchers define cost, on-time delivery and quality as primary performance metrics (Agarwal et al. 2006). Other researchers added productivity and safety to the metrics (Allen et al. 2001) . Levinson and Rerick (2002) defined Manufacturing Cycle Efficiency (MCE) and Fogarty (1992) defined Value-Added Efficiency (VAE) as performance metrics. Also, Daum and Bretscher (2004) defined a qualitative performance metric due to the different impressions of decision makers on the same outcome. Amin and Karim (2013) also selected a set of performance metrics from financial, quality, productivity, safety and flexibility measures categories.

This emphasises the necessity of identifying a set of lean performance metrics that is related to the organisation's goals and satisfies the requirements of the decision makers. To develop a set of performance metrics, first it is essential to understand these metrics and convert the well-understood and well-documented data into metrics. After identifying an appropriate set of performance metrics, decision makers and managers are asked to assign relative importance values to each metric using the tables provided in Appendix A (Koskela 1992; Ballard & Howell 1994; Gautam & Singh 2008; Amin 2012).

3.4.2 Identifying manufacturing wastes

To understand the entire production process and identify manufacturing problems, value stream mapping, production process investigation and video recording are utilised. In this regard, this research study defines the most common manufacturing wastes from the identified manufacturing problems. These wastes are failure time, work-in-process (WIP), final product inventory, raw material inventory, overprocessing, unnecessary movements, unnecessary transportation, setup time, knowledge disconnection and defects (Ohno 1988; Hines & Rich 1997; Ramesh & Kodali 2012; Amin & Karim 2013). After defining the manufacturing wastes, the relative importance values are allocated to each waste by the decision makers in the organisation. The decision-making team use a guideline provided in Appendix A to assign the importance value index to the wastes.

3.4.3 Identifying lean strategies based on identified performance metrics and production wastes

Several lean tools and techniques have been proposed and introduced to assist manufacturers in implementing the most efficient and effective manufacturing practice in their organisation (Shah & Ward 2007; Tiwari et al. 2007). Due to the competitive market environment, several organisations have adopted some lean strategies in the hope of achieving leaner production performance. Misapplication of lean strategies without understanding the purpose of these tools can fail and add more non-value-adding activities to the performance. Therefore, to achieve successful implementation of lean initiatives and improve the overall proficiency of the organisation, it is essential to understand the functional aspect of each lean manufacturing tool and select an appropriate set of lean strategies.

In this regard, this research study selected the most important lean techniques based on impacts on the identified performance metrics and wastes from an extensive literature review. These lean tools are 5S, Total Productive Maintenance (TPM), JIT, Total Quality Management (TQM), Kanban, Production Smoothing, Standard Work Process, Visual Management System, Cellular Manufacturing, Single Minute Exchange of Die (SMED), Safety Improvement Program and Information Management System. Chapter 2 presented detailed descriptions of these tools.

3.4.4 The impacts of lean strategies on identified performance metrics and manufacturing wastes

In this section, the influence of each lean strategy on identified manufacturing wastes is determined. These correlations are based on an extensive literature review and the definition of each tool and manufacturing waste. A similar approach was used by Hines and Rich (1997) and in the previous section to assign the correlation values for lean tools and manufacturing wastes. Lean tools with a high correlation with manufacturing wastes are ranked 3 and lean tools with medium and low correlation with manufacturing wastes are ranked 2 and 1 respectively. Lean strategies with low or negative correlation are assigned zero. These relationships and rankings are explained below.

3.4.4.1 5S

The 5S initiative helps manufacturers to clean and organise the manufacturing facility regularly by defining five main steps: sort, set in order, shine, standardise and sustain (Chapman 2005). Thus, the products and equipment can be found easily during operations. In this regard, this strategy can be beneficial in reducing unnecessary movements by workers in the production plant. This waste is related to the ergonomics of the manufacturing process. In these kinds of motions, operators must walk around the manufacturing plant to pick up equipment or to transport inventories to another place. Therefore, it is considered as a non-value-adding activity to the manufacturing process and affects the efficiency of the production process (Hines & Rich 1997; Saurin et al. 2010; Amin & Karim 2013). Hence, 5S can significantly reduce unnecessary movements for finding objects and have a high correlation with this waste (score 3). Moreover, this initiative has an impact on reducing setup time by streamlining the production process. This waste refers to the duration of manufacturing preparation activities, such as loading raw material, preparing equipment required, waiting for raw material or equipment, to start producing a product

(Hines & Rich 1997; Chahal & Narwal 2017). Therefore, 5S helps workers to find the required tools and materials when starting a machine. Thus, this initiative has a medium impact on changeover time (setup time) (score 2). In addition, the 5S principle can help employees to identify any problems in the machines. Therefore, 5S has a low impact on failure time (score 1). This waste refers to any manufacturing system breakdown (Hines & Rich 1997).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
5S	3	2	0	0	0	0	1	0	0	0

In addition, 5S principles often affect transportation, number of work-related injuries and on-time delivery by streamlining and organising the manufacturing unit as well as standardising the production process (score 3). Also, 5S is assigned scores of 2 for their correlation with manufacturing lead time and labour productivity and score of 1 for cost per part by rearranging the production process in a sequence to smooth the material and equipment flow and minimise the transportation and delays (Manotas Duque & Rivera Cadavid 2007; Anand & Kodali 2008; Raja 2011).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
5S	1	0	3	0	2	2	0	0	0	3	0	3

3.4.4.2 Total Productive Maintenance (TPM)

This initiative increases the equipment efficiencies and manufacturing system availability and reliability by conducting regular maintenance programs. Therefore, this preventive maintenance program results in decreased failure and breakdown in the manufacturing system. Therefore, this principle has a significant impact on failure time (score 3) (Hines & Rich 1997; Chahal & Narwal 2017). In addition, TPM has correlation with defects which happen due to failures in the production system and customers do not wish to pay for them. This strategy helps to eliminate this waste by increasing the reliability of the manufacturing system and reducing machine failure (Hines & Rich 1997). Hence, TPM has a low relationship with defects (score 1). Moreover, setup time can be reduced by carrying out regular proper maintenance programs and increasing the reliability and efficiency of the machines and tools in the production systems (Smith & Hawkins 2004). However, this initiative has an insignificant impact on setup time (score 1).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
TPM	0	1	1	0	0	0	3	0	0	0

TPM is a lean practice that focuses on optimising and increasing the efficiency and reliability of the equipment to avoid any breakdowns or delays in the production process (Dennis & Shook 2007; Anand & Kodali 2008; Ahuja 2011). Therefore, this strategy is assigned a score of 3 for overall equipment efficiency (OEE). Also, TPM involves all employees in the productive and preventive maintenance programs that can sometimes improve labour productivity (Singh et al., 2006). In addition, TPM sometimes can influence On-time delivery (OTD) by avoiding delays and breakdowns in the manufacturing process through preventive maintenance (Manotas Duque & Rivera Cadavid 2007; Ahuja 2011). Therefore, this practice has a medium correlation with labour productivity, rework rate and OTD (score 2). Moreover, Total Productive Maintenance (TPM) can sometimes reduce manufacturing lead time by preventing any delays caused by equipment or machine breakdown or defects and safety issues in the production process (Singh et al., 2006). Also, this tool attempts to improve the quality of the products, which can sometimes lead to customer satisfaction (Suzaki 1985; Cua et al. 2001; Smith & Hawkins 2004). Thus, this strategy has low correlation with manufacturing lead time and customer satisfaction metric (score 1).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
TPM	0	0	0	0	1	2	3	2	1	0	0	2

3.4.4.3 Just- In- Time (JIT)

This principle can significantly shorten the manufacturing process by producing required parts at the required time and maintaining the inventory at the minimum level. The main purpose of Just-In-Time (JIT) is to reduce the inventory level such as final products inventory, raw materials inventory and WIP. Final goods inventory refers to finished products that are stored at the end of the manufacturing process before delivery to the customer (Chahal & Narwal 2017). In addition, JIT focuses on decreasing the costs associated with storing raw materials before manufacturing products (raw materials inventory) and the storing cost of products that still require a production process (WIP) (Hines & Rich 1997; Chahal & Narwal 2017). Therefore, JIT has a high correlation with this waste (score 3). Sometimes defects can happen due to materials expiration. The JIT principle can reduce the number of defects by decreasing all types of inventory and avoiding them expiring. Therefore, this initiative has a low correlation with defects (score 1).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
JIT	0	0	1	0	3	0	0	3	3	0

Moreover, JIT principles can considerably affect financial metrics by reducing waiting time and overproduction and introducing a system that produces the required products at the necessary time. This initiative attempts to organise and streamline the manufacturing unit and prevent any delays, transportation and failure during the production operations (Cua et al. 2001; Ward & Zhou 2006; Manotas Duque & Rivera Cadavid 2007). It also focusses on shortening the manufacturing lead time and producing necessary products at the necessary time while keeping the inventory level to a minimum. Therefore, this initiative has a high correlation with the cost per part, total inventory cost, transportation cost, manufacturing lead time and on-time delivery (score 3). In addition, this lean strategy helps manufacturers to manage the supply and demand in the production line to produce the necessary product at the required time and quantity. JIT has a medium impact on supplier responsiveness (score 2).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
JIT	3	3	3	0	3	0	0	0	0	0	2	3

3.4.4.4 Total Quality Management (TQM)

The Total Quality Management (TQM) strategy utilises effective feedback from employees to improve the quality of the products by continuous improvement programs (Reid 2006; Bayazit & Karpak 2007). These improvement programs could have an impact on the quality of the product and, consequently, reduction in defects. Therefore, the TQM strategy is considered to have a high correlation with defects (score 3). In addition, the primary focus of TQM is on customer satisfaction and quality, which hold every employee to account for maintaining the quality level of products. This requires collaboration between all employees and managers at all levels (Reid 2006). Inappropriate processing consists of any activities that is not significant for producing the final product (Hines & Rich 1997; Raja 2011). Therefore, TQM could have a low correlation with over processing (score 1) by involving employees to identify over processing steps in the manufacturing process (Chahal & Narwal 2017).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
TQM	0	0	3	0	0	1	0	0	0	0

In addition, one of the concepts of TQM is to measure the satisfaction level of internal and external consumers on a periodic basis (Bayazit & Karpak 2007). This initiative uses effective feedback in the continuous improvement program to improve the quality of the product and consequently customer satisfaction. Also, this strategy continuously improves the production process to improve the quality of the products (Terziovski & Samson 1999; Cua et al. 2001). Therefore, this lean practice has a high correlation with rework rate and customer satisfaction metric (score 3).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
TQM	0	0	0	0	0	0	0	3	3	0	0	0

3.4.4.5 Pull/Kanban system

Similar to the JIT principle, Kanban is a signalling method with the aim of reducing all kinds of inventories by specifying the number of products required to be produced. Therefore, this initiative has a high correlation with the final product inventory, raw materials inventory and WIP (score 3). It has a low correlation with defects (score 1) by reducing the number of inventories at every stage of the production process and avoiding the expiration of products.

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
Kanban	0	0	1	0	3	0	0	3	3	0

Moreover, the Pull or Kanban system aim to decrease inventories to the minimum level; thus, they have a high correlation with the total transportation cost (score 3). As mentioned in the literature review chapter, Kanban is a system of signalling cards that determine the products required to be produced with the aim of reducing all types of inventories in the manufacturing process. This initiative attempts to organise the production process to avoid any delays, excess transportation and failure during the manufacturing operations. Therefore, this strategy has a high correlation with setup time and on-time delivery (score 3). In addition, Kanban is a system of signalling cards to improve the material, equipment and information flow in the production line. Therefore, it usually enhances the ability of manufacturers to manage their supply chain (Hobbs 2004; Manotas Duque & Rivera Cadavid 2007). Hence, this tool is assigned score of 2 for manufacturing lead time and supplier responsiveness.

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
Kanban	0	3	0	3	2	0	0	0	0	0	2	3

3.4.4.6 Production Smoothing

According to Ohno (1988), the production smoothing strategy aims to maintain the production process rate to a constant level with the primary goal of reducing finished goods inventory, and checking and reworking of products (Suzaki 1985). Therefore, the correlation between this initiative and final goods inventory is considered to be high (score 3). In addition, a constant rate of production leads to a reduction of raw materials inventory as well as WIP for particular products. Therefore, this lean strategy has a medium correlation with raw materials inventory and WIP (score 2). Similar to the JIT and Kanban systems, production smoothing can have a low impact on the defect rate by reducing inventories level and preventing them from expiring. Hence, production smoothing has a low correlation with defects (score 1).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
Production smoothing	0	0	1	0	3	0	0	2	2	0

The aim of Production Smoothing is to reduce inventory handling and to check pact on the rework rate by improving the efficiency and reliability of the equipment and machines to avoid any breakdowns or defects (Ahuja 2011). Therefore, it has a high correlation with rework rate (score 3). In addition, Production Smoothing aims to reduce the cost of inventory handling by streamlining the production process and smoothing the material and equipment flow (Suzaki 1985;

Abdulmalek & Rajgopal 2007). Therefore, this initiative is assigned score of 2 for total inventory cost.

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
Production smoothing	0	2	0	0	0	0	0	3	0	0	0	0

3.4.4.7 Standard Work Process

Standard work process introduces a standard procedure for employees to follow to control and simplify the production process. Therefore, this principle adds more value to the production process by transforming complex procedures to simple and standard procedures. As a result, this principle has a high correlation with over processing (score 3). In addition, this principle aims to reduce every kind of variability in the organisation. By following standard processes, workers can help reduce manufacturing variabilities and this has considerable impacts on unnecessary movements, setup time and failures (Arnheiter & Maleyeff 2005). As a result, this lean strategy is given a score of 2 with respect to unnecessary movements, setup time and failure. In addition, standardising the production process can sometimes lead to a reduction of unnecessary transportation in the manufacturing facilities. This waste refers to material and workers' transportations around manufacturing facilities that do not add value to the final product and may sometimes cause damage or delay to the product. Thus, Standard Work Process has a low correlation with unnecessary transportation (score 1).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
Standard work process	2	2	0	1	0	3	0	0	0	0

Furthermore, standard work process principles help manufacturers to reduce manufacturing variabilities to decrease the total manufacturing cost. This lean initiative reduces these variabilities by introducing a standard procedure for employees to follow and control the production process, add more value to the operation and meet customer requirements (Arnheiter & Maleyeff 2005). Therefore, this lean strategy has a high impact on cost per part and customer satisfaction metrics (score 3). Also, standard work process has a medium correlation (score 2) with transportation cost by streamlining and organising the manufacturing unit as well as standardising the production process. The Standard work process also has a low correlation (score 1) with rework rate by decreasing manufacturing variability (Manotas Duque & Rivera Cadavid 2007).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
Standard work process	3	0	2	0	0	0	0	1	3	0	0	0

3.4.4.8 Visual Management System

This principle helps manufacturers to understand and control the activities in the manufacturing plant and can sometimes lead to a reduction in unnecessary movements (Saurin et al. 2010). Therefore, the Visual Management System has an average effect on excess movements (score 2).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
Visual management system	2	0	0	0	0	0	0	0	0	0

In addition, Visual control enablers indicate safety lines and the location of tools in the manufacturing line (Manotas Duque & Rivera Cadavid 2007; Hill 2011). Therefore, they can sometimes reduce the number of injuries in the factory (score 2).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
Visual management system	0	0	1	0	0	0	0	0	0	2	0	0

3.4.4.9 Cellular Manufacturing

This initiative helps manufacturers streamline the production process and plant facility layout. This transformation helps to considerably reduce transportation time of tools, materials and employees from one station to another (Suzaki 1985; Bn 2008). Therefore, the Cellular Manufacturing strategy has a high impact on unnecessary movements and transportation wastes (score 3). In addition, Cellular Manufacturing emphasises reducing inventory, especially WIP. Thus, this lean tool has a medium impact on WIP inventory (score 2) (Chahal & Narwal 2017). Finally, Cellular Manufacturing can sometimes help manufacturers and shop floor staff to reduce the duration of setup activities (Heragu 1994). Therefore, it is given a score of 1 in relation to setup time.

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
Cellular manufacturing	3	1	1	3	0	0	0	2	0	0

Furthermore, Cellular Manufacturing can help manufacturers to reduce costs associated with transportation, as their primary focus is to shorten the manufacturing lead time and transportation time in the manufacturing line and, subsequently, transportation cost. This initiative reduces delays and transportation time in the production line by organising and streamlining the production facilities and physical configuration of the plant, which can lead to manufacturing lead time reduction. Also, implementing Cellular Manufacturing in the production line usually results in reducing labour expenditure considerably and consequently improving labour productivity (Heragu 1994). Therefore, this lean strategy has a high impact on transportation cost, manufacturing lead time and labour productivity (score 3). In addition, Cellular Manufacturing aims to reduce the cost of inventory handling by streamlining the production process and smoothing the material and equipment flow (Suzaki 1985; Abdulmalek & Rajgopal 2007). Therefore, the correlation between Cellular Manufacturing and total inventory cost is scored 2. Cellular Manufacturing can only sometimes reduce the manufacturing cost and rework rate by rearranging the production process in a sequence to smooth the material and equipment flow and minimise the transportation and delays (Manotas Duque & Rivera Cadavid 2007; Anand & Kodali 2008; Raja 2011).

Cellular Manufacturing can sometimes affect overall equipment efficiency by creating product families and equipment families that can result in better machine and equipment utilisation (Heragu 1994). Also, it attempts to improve the quality of the products, which can sometimes lead to customer satisfaction (Suzaki 1985; Smith & Hawkins 2004). Thus, this strategy has low correlation with cost per part, OEE, rework rate and customer satisfaction metric (score 1).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
Cellular manufacturing	1	2	3	0	3	3	1	1	1	0	0	0

3.4.4.10 Single Minute Exchange of Die (SMED)

The Single-Minute Exchange of Die (SMED) lean strategy is utilised to analyse and redesign the activities associated with setup and changeover time. This initiative reduces the waiting time related to setups by redesigning the process, equipment and tools. Therefore, SMED has a high correlation with setup time (score 3).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
SMED	0	3	0	0	0	0	0	0	0	0

In addition, SMED is a lean initiative that mainly focuses on principles to reduce setup time and redesign the setup process, tools and equipment to reduce the waiting time related to setups (Agustin & Santiago 1996). Therefore, this initiative is assigned a score of 3 for setup time and score of 2 for manufacturing lead time.

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
SMED	0	0	0	3	2	0	0	0	0	0	0	0

3.4.4.11 Safety Improvement Program

This principle helps manufacturers to reduce work-related injuries and manufacturing system breakdowns through continuous improvement programs. Therefore, this initiative is given a score of 3 with respect to failure time reduction.

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
Safety improvement program	0	0	0	0	0	0	3	0	0	0

Moreover, Safety Improvement Programs implement a continuous improvement approach to safety to increase the safety level of the production line. Therefore, this practice has a high correlation with the number of work-related injuries metric (score 3).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
Safety improvement program	0	0	0	0	0	0	0	0	0	3	0	0

3.4.4.12 Information Management Systems

As explained in Chapter 2, an Information Management System facilitates the information flow in the manufacturing firm. These data are usually associated with material and tools data, quality data and operators' information. Therefore, this initiative has a high correlation with the knowledge disconnection waste (score 3).

	Unnecessary movement	Setup time	defects	Unnecessary transportation	Final good inventory	Over processing	Failure time	WIP	Raw Material inventory	Knowledge disconnection
Information management systems	0	0	0	0	0	0	0	2	2	3

Furthermore, Information Management Systems help managers to streamline the information flow in the organisation, including suppliers' responsiveness. Thus, this initiative has a high correlation with supplier responsiveness (score 3) and medium correlation with on-time delivery (score 2) and low correlation with total inventory cost and manufacturing lead time (score 1) (Manotas Duque & Rivera Cadavid 2007).

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time delivery
Information management systems	0	1	0	1	0	0	0	0	0	0	3	2

3.4.5 Converting established relationships between lean tools, performance metrics and wastes to binary numbers

After establishing the correlation matrix between lean tools and performance metrics, these relationships are simplified by solely considering strong relationships between lean tools and performance metrics. A binary correlation among lean strategies and metrics, where those lean strategies which have a high impact on a performance metrics (value is at least 3) are assigned 1, otherwise it is allocated 0, as presented in Table 3.1. Establishing a binary correlation matrix simplifies the decision making to suggest proper set of lean tools with a significant influence on identified performance measures.

In addition, the relationships presented in Section 3.4.4 are simplified by considering the maximum correlation between lean tools and manufacturing wastes. This method can help manufacturers to select a set of lean techniques that have significant relationships with identified wastes. Therefore, a relationship matrix between lean strategies and manufacturing wastes using binary numbers has been developed and is presented in Table 3.1. According to this table, the relationship value between one lean strategy and a manufacturing waste is 1 if this strategy has significant impact on a waste (score 3); otherwise, it is considered 0.

Table 3.1: Binary impacts of lean tools on performance metrics and manufacturing wastes

Knowledge disconnection	Raw material inventories	WIP	Failure time	Over processing	Final goods inventory	Unnecessary transportation	defects	Setup time	Unnecessary movements	Manufacturing wastes / Performance metrics	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	Number of work related injuries	Supplier responsiveness	On-time Delivery
0	0	0	0	0	0	0	0	0	1	5S	0	0	1	0	0	0	0	0	0	1	0	1
0	0	0	1	0	0	0	0	0	0	TPM	0	0	0	0	0	0	1	0	0	0	0	0
0	1	1	0	0	1	0	0	0	0	JIT	1	1	1	0	1	0	0	0	0	0	0	1
0	0	0	0	0	0	0	1	0	0	TQM	0	0	0	0	0	0	0	1	1	0	0	0
0	1	1	0	0	1	0	0	0	0	Kanban	0	1	0	1	0	0	0	0	0	0	0	1
0	0	0	0	0	1	0	0	0	0	Production smoothing	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0	0	0	Standard work process	1	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	Visual management	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	1	Cellular manufacturing	0	0	1	0	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	SMED	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	Safety improvement system	0	0	0	0	0	0	0	0	0	1	0	0
1	0	0	0	0	0	0	0	0	0	Information flow management system	0	0	0	0	0	0	0	0	0	0	1	0

3.4.6 Finding the optimum selection of lean initiatives

In the last two sections, ten manufacturing wastes and twelve lean performance metrics were identified. However, due to resource constraints, such as budget and time limitations, it is not easy to choose and suggest lean tools that increase the perceived value index to its maximum value for the manufacturing line. Therefore, it is vital to prioritise the selected manufacturing wastes and performance metrics by allocating relative importance values to each metric and waste. These values are given by decision makers and the management team based on their priorities in improving performance indicators and addressing production problems after extensive analysis of these factors. In this respect, executive managers and decision makers require instructions (provided in Appendix A) to rank these factors.

As mentioned earlier in this chapter, Equation 3.1 is used to calculate a lean strategy implementation perceived value. It is also essential to consider the overall calculation of the perceived value if any waste or performance metric is addressed by more than one lean strategy. For instance, in Table 3.1, it is presented that on-time delivery has a high correlation with 5S, JIT and the Kanban system.

In this chapter the lean strategy selection approaches considering the correlation between lean tools, performance metrics and manufacturing wastes has been developed. The model was developed using MATLAB and an Excel spreadsheet. This model and methodology help manufacturers to select the most appropriate lean strategies for improving performance metrics as well as eliminating manufacturing wastes. The results obtained from the proposed methodology is more accurate as the developed methodology suggest the best set of lean tools for implementation that not only reduce the critical manufacturing wastes but also significantly improves the critical performance metrics.

3.5 Application of the proposed methodology in a real-life case study

The case study approach is a perfect method for comprehensively investigating the model and methodology, therefore, the developed model and methodology have been tested using a real-life case study and also provided a guideline for implementing the developed models.

3.5.1 Techniques for data collection

Various techniques were used to collect data for the purpose of this research and the following section presents a description of these data collection techniques.

Data collection techniques	Description
Literature review	The literature review is a primary approach to recognise, assess and understand the body of knowledge of the subject (Fink, 2010). A literature review helps researchers to understand the current concepts in a particular area and find out new ideas (Burns, 1997). The literature review revealed clear limitations in the lean strategy selection approach as well as leanness assessment models. Different lean strategy applications will be reviewed to understand the effect of various lean strategies on each performance metric to develop a correlation matrix between lean tools, performance metrics and production problems. Several leanness measurement models were also reviewed for this study. In this research, the relationships of lean tools, performance metrics and manufacturing wastes will be investigated using the literature review for further extension of the lean tools selection approach and

	an appropriate set of performance metrics will also be determined using the literature review.
Informal meetings	Informal meetings took place during the data collection stages using a case study company. The informal meetings were conducted with the aim of building a relationship between the researcher and employees/managers within the case study organisation. These meetings focused on work-related issues of the employees/managers. The reliability of this technique depends on the cooperation of the shop floor staff and their feedback. However, if the staff felt disturbed at any time during the meetings, which affected their normal tasks, their answers were omitted from the data collection process. Hence, building a cooperative relationship with the case study organisation was critical in the early stages of the research.
Company investigation and VSM	Company investigation provided an opportunity for the researcher to observe the production activities and be able to assess the general production issues visually within the case study company. After completing the informal meetings, a direct observation of the production process and organisation's system was carried out by the researcher. This made the researcher familiar with the details of the production process, organisational environment and systems as well as the management team involved in the lean strategy implementation. After observing the company's production process, the researcher became familiar with the manufacturing process, the material, the nature of modular manufacturing industry and their supplier and customer and consequently was able to identify the links between employees, the organisation's manufacturing process and its flow. During the company investigation and observation, different value streams were identified. These value streams are different manufacturing processes running in this company. The site manager illustrated different production

lines in the facility. Each value stream was designed to complete specific and different projects for different customers. Therefore, few value streams were selected for further discussion with top managers at the unstructured interviews. However, during the unstructured interviews, only one value stream was selected for the purpose of this research based on the criticality of the selected stream. The selection of the value stream was based on the management team and their preferences in optimising the specific value stream and reducing wastes in that stream. Therefore, the proposed lean strategies selection model and the weighted leanness assessment model were used for the selected value stream.

Moreover, during the company's observation and investigations the author used video recording to collect data related to the manufacturing process. As the sequence of the construction is unlikely to be repeated on a regular basis, the researcher used video footage for recording some part of the manufacturing process to store and analyse at a later time. Using the recorded videos, the researcher was able to define the performance metrics for the selected value stream, which is workstation 4 in this research (see Table 3.2 and Table 4.3). Also, the researcher identified the manufacturing problems, such as long waiting time and equipment handling issues (please see section 3.5.5.3 for more manufacturing problems), and later defined the manufacturing wastes for workstation 4 during the company observation (Table 3.3). Also, video recording were used to draw the current state map of the selected value stream (QMC manufacturing line), which is illustrated in Figure 3.2, and the current state map of work Station 4, which is presented in Figure 3.3.

Furthermore, the researcher used company observation to measure some performance metrics, such as setup time, manufacturing lead time, on-time delivery, labour productivity and rework rate. Using observation and company

	investigation, the researcher was able to complete Table 4.5, which is the main input for the proposed weighted leanness assessment model. Also, these data were used for calculating the correlation coefficient value of lean performance metrics as a direction for Analytic Network Process (ANP), which allocated interrelationships weights to each performance metrics.
Unstructured interviews	Unstructured interviews took place during the data collection stages at the case study company. The researcher carried out unstructured interviews with managers and decision makers to gather general information on the production process. Meanwhile, before starting the interviews with managers, the author prepared a brief description of each performance metric and manufacturing waste to provide them with a general understanding of each term. The data collected from the unstructured interviews contain information about the manufacturing process in each workstation, challenges in the manufacturing process starting from supplier and ending at the customer, identification of lean implementation factors, performance metrics as well as the level of implementation of lean tools. Also, in these interviews the concept of lean manufacturing, criticality of manufacturing wastes and performance metrics were discussed. Furthermore, in these interviews, the author and management team came to a conclusion to select one particular value stream to focus on for the purpose of this research based on the criticality of the selected value stream. Also, the author asked the manager related to the manufacturing process to rank and prioritise the identified performance metrics and manufacturing wastes. In addition, during the unstructured interviews the research and management team concluded to select worktation 4 to the purpose of the study due to the criticality and the amount of wastes identified in this station.

	Also, in these interviews the cost and time budget for implementing lean tools were discussed with the decision makers and top management team. These collected data were used as constraints for the proposed lean strategies selection methodology (Table 3.6). Some of the questions that were asked during the unstructured interview included, what are the critical manufacturing wastes among the identified wastes at this stage? What are the critical performance metrics for the selected value stream? What is the company cost and time limitation for implementing the selected lean tools? How many suppliers does the project have? What is the deadline for delivering the project?
Archival data	During the data collection process, archival records were used to collect data related to qualitative and quantitative performance metrics such as cost per part, total inventory cost, transportation cost, Overall Equipment Efficiency, customer satisfaction, number of work-related injuries and supplier responsiveness. Archival data was also used for extracting information about the types of manufacturing wastes. Different problems that have previously occurred in the production process may be found in the database of the company. For instance, the frequency of the delay in project delivery, the occurrences of shop floor staff injuries, the incidences of delays in delivery of raw materials from the supplier, and amount customer feedback. For these record, the author was able to assess the supplier responsiveness, the safety level of the manufacturing facility, customer satisfaction and on-time delivery.

3.5.2 Data analysis tools

The tools and techniques used for the data analysis process for the purpose of this research will be described in this section. MATLAB, Microsoft Access, and Microsoft Excel were utilised to achieve the second research objective.

Tools	Description
MATLAB	A MATLAB programming code was generated for developing a correlation matrix between lean tools, manufacturing wastes and performance metrics to select and suggest the proper set of lean tools. These tools have the most significant impacts on an organisation's critical wastes and performance metrics and the correlation matrix represents which lean tools have a direct impact on which metrics and wastes. An Excel spreadsheet is used to save all the relationships and is imported to MATLAB to find the optimum solution. In MATLAB, the effects of variation in one performance metric on other metrics can be simulated and observed. The interrelationships between performance indicators have effects on the leanness assessment process. Hence, to achieve the second objective of this research, the MATLAB programming code was used to develop the weighted leanness measurement methodology. This model will help the manufacturer to consider the interrelationships between lean performance metrics.
Microsoft Excel	Microsoft Excel and Microsoft Access were utilised to manage the data in this research. The software sorted all the inputs and outputs for the proposed models. The data from the Excel spreadsheets were exported to MATLAB software. Microsoft Excel was also used to categorise production activities into value-adding and non-value-adding activities.

The next section describes the application of the proposed lean tools selection method in the real-life case study for the modular construction company.

3.5.3 Background of case study company

The HMC[5] company is one of the leading modular manufacturers in Australia. The company was founded in 1912 and has over 1400 employees. HMC has expanded its market to construct several types of buildings for different sectors such as mining infrastructure, education, mixed use, health, residential, commercial, hospitality and tourism, retail, community, government and industrial. In addition, the company provides a variety of services including construction, design, cost planning, project finance, civil works, green star, quality assurance, cranes and hoists, modular, heritage and restoration, facilities management and training. The company uses modular construction to describe a building process regardless of uncertainties in weather, site conditions and contractor relations. The HMC company has three large modular manufacturing facilities in Australia. The modular facility selected for the purpose of this study can produce 3000 rooms per year with varying specifications to cater for acoustic control, energy efficiency, fire separation and a general industry requirement for a higher standard of accommodation to assist mining companies maintaining staff in remote areas.

Despite modularisation providing significant competitive benefits in site construction time, quality control and predictability, the company has not yet reaped the full benefits of modularisation. The products of this company were typically 10-20% more expensive than their counterparts built on site due to transportation and installation costs. Therefore, their customers are primarily limited to government and education sectors that are less concerned about the cost of the project. The main reason for increasing the total cost of products was that this company, like other modular manufacturers, still builds the units on the roof using conventional construction methods and fails to take advantage of modern manufacturing technologies to improve their production process considerably.

Therefore, to stay competitive in the market, the top managers are keen to adopt and implement lean manufacturing strategies to reduce any possible inefficiencies in the production process and improve its quality and productivity. Previously, the company attempted to implement some lean

[5] Due to confidentiality reasons, the research cannot disclose the company name and HMC is an assumed name

strategies in the manufacturing process, such as Cellular Manufacturing and TQM. However, they did not achieve significant benefits from the lean strategies implementation mainly due to the misapplication of the lean tools. In the past, the management team believed that implementing any lean strategies would minimise the number of resources and reduce manufacturing wastes, without considering the cost and time associated with lean strategies implementation. They also did not recognise that implementing lean tools requires the participation and involvement of all employees from the management level to shop floor staff, as well as a transformation in the organisation's culture and structure. Their decision for implementing lean strategies was based on management's judgment and preferences and they ignored several important factors for selecting lean strategies. In addition, they were unable to measure the benefits achieved by implementing lean strategies and the improvement in the production line was not visible to the decision makers.

Hence, after they realized that misapplication of lean strategies can increase the costs as well as non-value adding activities, they decided to select lean strategies systematically and measure the improvement achieved through adopting and implementing lean manufacturing tools. Therefore, the problem in this company was to select lean strategies as well as measure the current and optimum leanness level of the production process. In this regard, this section explains the application of the proposed model for selecting proper lean strategies based on their correlation with manufacturing wastes and performance metrics as well as the developed model to measure the leanness index of the production line considering the interdependent relationships between lean performance metrics. For this purpose, a lean project team was selected to clarify the research scope and identify the critical performance metrics and manufacturing wastes.

3.5.4 Defining appropriate scope for the project

After selecting project team members, the scope of the study could be identified. The team decided to use the proposed methodology and model for selecting the most appropriate lean strategies based on the relationships between lean tools, performance metrics and manufacturing wastes for their QMC modular line. After discussion with the management team of the case study company, it was recognised that this line could achieve significant benefits from implementing lean strategies. A QMC modular line is a manufacturing line for producing prefabricated modules. This line is designed to manufacture prefabricated units for a two-story student accommodation building. Each module is built under the roof in the factory and shipped to the site. These units are stored inside the factory and labour and material goes through a construction process, similar to the conventional construction process. The lean team used a value stream mapping (VSM) tool to draw the current state map of this manufacturing line. The main purpose of this step was to identify the non-value adding activities and production problems that lead to unusual states as well as identifying relative performance metrics.

Figure 3.2 shows an overall picture of the QMC modular manufacturing line of the HMC company with critical information of the current operations. In this figure, C/T refers to production cycle time of the station, which is a processes of cycle time that a product must pass to become a final product. C/O refers to changeover time that is defined as the process of changing a line or machine from running one product to another. In the current state map, raw material inventories are stored for three to four days before being withdrawn for the manufacturing process based on the weekly schedule. The QMC manufacturing line starts from the loading chassis and installation of floor sheets, wall and roof frames at Station 1 as well as installing the electrical and mechanical services. Then, at Station 2 the internal ceilings and external walls are installed. Next, roof sheeting, external walls sheeting and external windows, shower wall systems and floor coverings are installed at Station 3. After completing the previous tasks, external and internal doors and leads are inserted at Station 4, the internal door units are painted, the underfloor is insulted and the electrical and mechanical rough conduits are installed. At workstation 5, underfloor hydraulics, joinery, shower screens and sundry hardware are installed. The internal and external parts are caulked and internal and external defects are rectified at Station 6. In this station each module is wrapped and strapped for transportation. Finally, the modules are stored after conducting a QA final inspection (Station 7).

From the current state map (Figure 3.2), it can be seen that the production cycle time (*C/T*) is much lower than the Takt time (T=480 min) in some stations. This shows that the production capacities of these stations are higher than the demand. Takt time (*T*) is the maximum time that a modular unit can stay in one station, which is calculated by dividing the net time available for work (T_a) by customer demand (D) using the following formula:

$$T = \frac{T_a}{D} \qquad \text{Equation 3.23}$$

However, it can be seen from Figure 3.2 that the completion rates in those stations were low. Completion rate refers to the percentage of modules that are moving to the next station while all tasks are completed. For example, at Station 3, the average cycle time is 400 min, which is 17% lower than the Takt time. However, the completion rate at this station is 80%, meaning that one of every five modules moves to Station 4 uncompleted. The completion rate at this station is noticeably low considering that the cycle time in this station is close to the Takt time. With regard to Station 5, the completion rate is 60%, meaning that almost half of all modules are unfinished when moving to the next station. This situation can affect the production process and increase different kinds of waste in the manufacturing company, such as unneeded movements by labourers as a result of not completing all tasks. For example, if electricians at workstation 4 cannot finish the rough conduit, they should finish their tasks at Station 5, which requires them to move and carry their equipment and materials between these two stations. Also, as they spend time to complete their tasks at Station 5, they would have less time at Station 4 for the next modules. In addition, workers at Station 5 have less time to complete their job before the module is moved to the next station as they were idle at the beginning. The relationship between the seven stations in the QMC manufacturing line is shown in Figure 3.2.

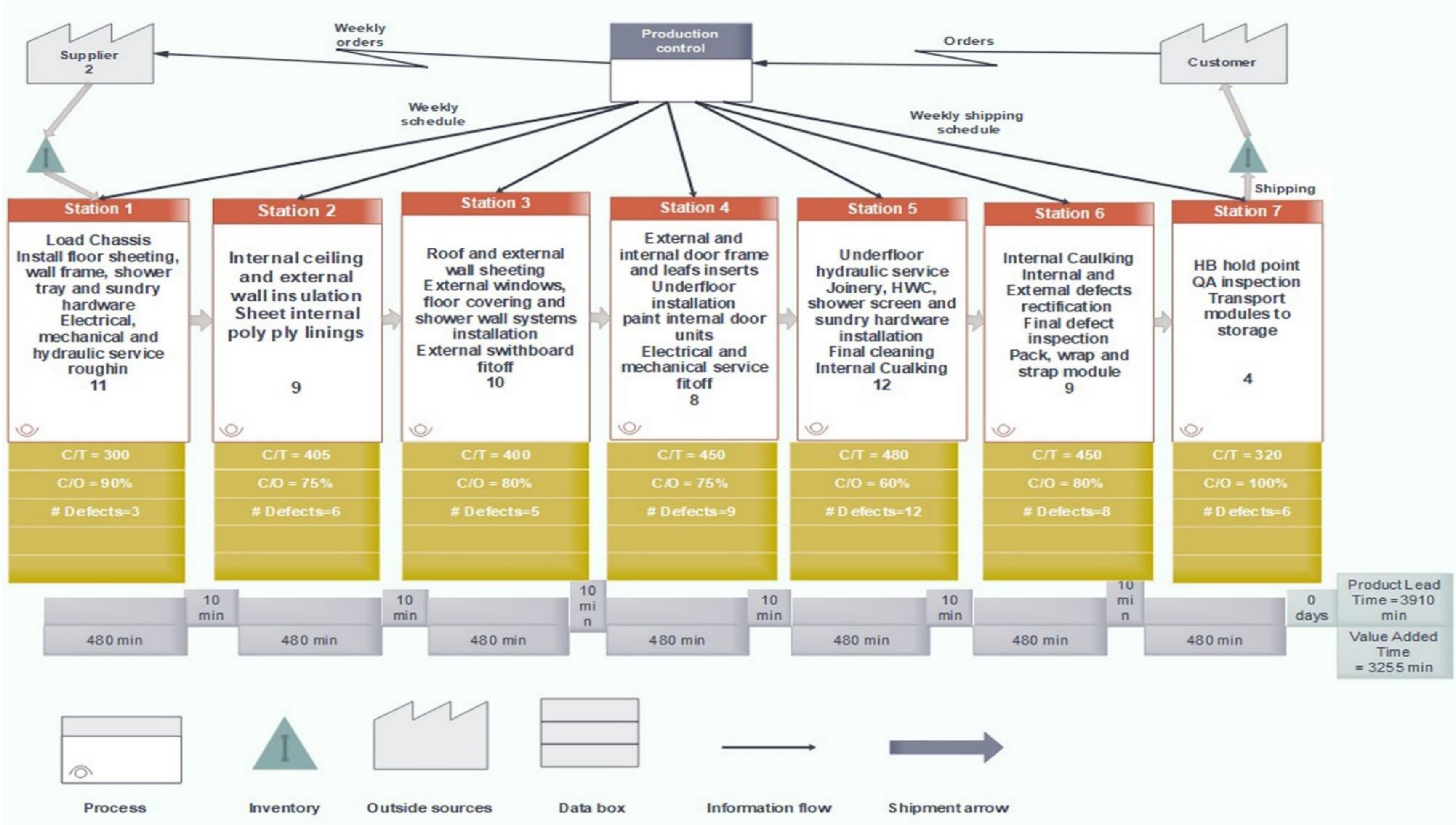

Figure 3.2: QMC manufacturing line's current state map.

The lean team and the HMC management team decided to concentrate on Station 4 as it is believed that this station is a barrier for this modular manufacturing line due to low efficiency in this station and interruption of the performance. The management team can extend this procedure to the other stations after the study. Due to the limited time of this research study, Station 4 was selected, and the lean strategies selection problem can be expressed as a lean strategies selection method based on the interrelationship between lean tools, performance metrics and manufacturing wastes to improve identified metrics and address manufacturing wastes. In Figure 3.3, the manufacturing line at Station 4 is examined in detail to understand the main operations of this workstation.

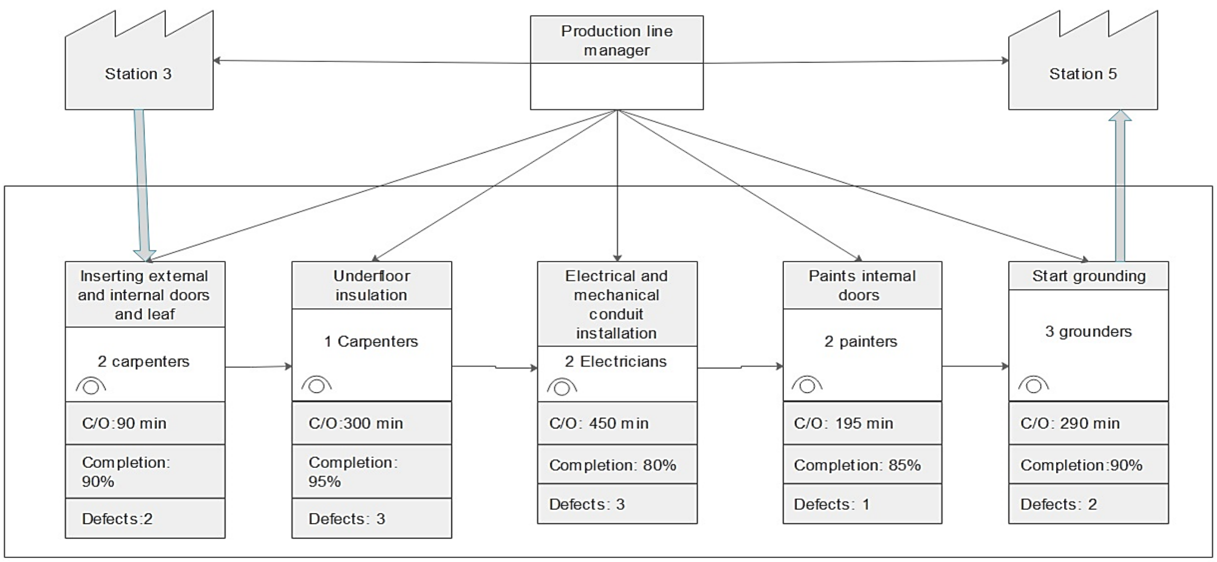

Figure 3.3: Current state map of Station 4.

3.5.5 Company investigation and production process observation to identify performance metrics and manufacturing wastes

To identify manufacturing problems and select an appropriate set of lean performance metrics, Value Stream Mapping (VSM) was selected due to its ability to link lean strategies to the whole process. During door-to-door production observations, the researcher noticed that VSM tools cannot identify some wastes and performance metrics in the manufacturing line. Therefore, other methods such as video recording, observations and unstructured interviews were conducted alongside VSM to determine other wastes in the modular production line. In addition, the researcher conducted informal meetings, extra observations and used archival data of the company to recognize the main source of these wastes at Station 4. In this respect, the main operations in this station were analysed to identify the production wastes and their primary sources. The major activities at Station 4 are:

- Inserting internal door frames and leaves
- Inserting external door frames and leaves
- Insulating underfloor
- Electrical service fit off
- Mechanical service fit off
- Painting internal door units

A time and motion study was conducted to identify value-adding and non-value adding activities in this manufacturing line. The main purpose of the time and motion study was to understand the work process and explore value-added time against non-value-added time. This method includes process recording, break downing the recorded time, categorising the process and identifying value-added and non-value-added time. This method helps researchers and manufacturers to understand the activities of all workers at a workstation in detail and identify problems and solutions as well as performance metrics. Other methods used to identify manufacturing wastes and performance metrics in this company detailed below:

3.5.5.1 Video recording of the process

To analyse the manufacturing process, video recording was used to identify problems at the workstation. video recording can be used to facilitate data collection of shop floor information as well as developing the analysis procedure to include ergonomic aspects and work performance in the analysis (Engström & Medbo 1997). As the manufacturing process in the case study company was run only once, the author had to record different parts of the manufacturing process to save the required information in the archive, and discuss the process in the meeting with managers and decision makers. Before starting the recording process, the lean team and the operators discussed the purpose and procedure of the video recording. The procedure of the video recording needed to be in such a way that it did not affect the normal flow of the production process. This helped the researcher to obtain accurate data from the manufacturing line. For this stage, a video camera was used to record the operations for Station 4 at the QMC manufacturing line.

3.5.5.2 Recorded time breakdown

The reordered video was analysed and the activities in the production process were divided by time sections.

3.5.5.3 Categorizing the process

Activities recorded during the recording process were grouped into value-adding and non-value-adding activities. After that, the lean team discussed these activities with the engineering manager and skilled operators to check and ensure that these operations were added to the correct category. Non-value-adding operations must be removed from the production line as they do not add value and increase wastes in the manufacturing line. These activities are walking to get parts and tools, handling, inspection, paperwork, cleaning, reworking and unpacking.

Therefore, in respect to workstation 4 in the QMC manufacturing line, the lean team identified the following activities that increase wastes in the company:

- Walking between stations to get parts and tools: labours walk from their station to get tools and materials and to complete their job at the next station. These walking times are non-value-adding activities which are considered wastes, such as unneeded movements and unnecessary transportation. It is also observed that tools are maintained inappropriately in workstation and also in the warehouse, which can cause transportation waste.
- Waiting time: operators sometimes wait for materials, tools and equipment or they are idle due to waiting for other operators from the previous station to finish their job. Also, sometimes workers have to wait for materials to be delivered to the company and often the suppliers are delayed in delivering the raw materials. Therefore, these periods are considered to be a waste.

- Handling: this problem is caused due to lack of experience of the labourer in handling or completing their job. Also, often workers require assistance from other workers in completing jobs. This causes inefficiency in the company and significantly reduces labour productivity.
- Reworking: this problem is associated with poor quality of modules that can significantly increase the WIP inventory level. In the selected manufacturing line, some materials are fragile and break during installation. This can increase the material wastes as well as increase the number of reworking.
- Facility layout design: the plant layout plays a significant role in transferring information between stations and has an effect on the production process flow. Therefore, inefficient factory layout can cause an increase in various wastes such as the walking distance between stations and information flow between departments. In the selected manufacturing line, some stations are under roof and others are located outside the facility due to lack of enough spare. Consequently, weather condition may affect the manufacturing process and can sometimes delay the process or damage the modules.

The next step after identifying the scope of the study and the manufacturing problems was to select a set of lean performance metrics that presented the direction of improvement during lean implementation. After several discussions with the lean team, management team and decision makers, financial, productivity, flexibility, quality and safety measures were selected for the production process at workstation 4. Therefore, the team decided to select eleven lean performance metrics at this stage. The complete list of performance metrics identified by several researchers is provided in Appendix B. These performance metrics are redefined for Station 4, considering Station 3 as a supplier, Station 5 as a customer and Station 4 as a manufacturing process. The selected lean performance metrics are cost per part, total inventory cost, transportation cost, setup time, manufacturing lead time, labour productivity, overall equipment efficiency, customer satisfaction, rework rate, number of work-related injuries, supplier responsiveness and On-Time Delivery (OTD).

3.5.6 Decision makers' opinion in assigning relative importance weights to lean metrics and wastes

The previous section explained the process of identifying manufacturing wastes and performance metrics at Station 4 in the QMC manufacturing line through observation, interview and informal meetings. As a result, the lean team and management team classified identified problems into ten manufacturing wastes and defined relevant lean performance metrics for this station. For this section, the lean team asked the executive team including the engineering manager and production director to rank identified wastes and performance metrics based on their priorities of reduction for manufacturing wastes and their importance for performance metrics. A guideline was provided for them to rank these factors as critical, significant, medium, low or unimportant. Appendix A presents the details of this guideline. The relative importance weights of performance metrics are presented in Table 3.2 and the priorities of the decision makers regarding manufacturing wastes reduction are provided in Table 3.3.

Table 3.2: Station 4's performance metrics with relative importance weightings

Performance measures	Performance metrics	Relative importance weightings
Financial	Cost per part	9
	Total inventory cost	7
	Transportation cost	8
Productivity	Setup time	9
	Manufacturing lead time	6
	Labour productivity	5
	Overall equipment efficiency	8
Quality	Rework rate	5
	Customer satisfaction	6
Safety	Number of work-related injuries	4
Flexibility	Supplier responsiveness	4
	On-Time Delivery (OTD)	5

Table 3.3: Station 4's manufacturing wastes with importance weightings

Manufacturing wastes	Relative importance weightings
Unneeded movements	9
Setup time	7
Defects	8
Unnecessary transportation	7
Final goods inventory	5
Over processing	7
Failure time	6
WIP	4
Raw materials inventory	4
Knowledge disconnection	5

3.5.7 Establishing relationship between lean strategies, performance metrics and manufacturing wastes

As mentioned earlier, the primary objective of this chapter is to suggest one or more lean strategies for implementation to improve identified performance metrics and address the manufacturing problems in the defined project scope. Each lean strategy has an impact on a particular performance metric and leads to a reduction of a specific manufacturing waste. Therefore, this section continues to develop the correlation matrix developed in section 3.4.4. by adding the relative importance weightings of performance metrics and manufacturing wastes.

Table 3.4, shows the correlation between lean tools, performance metrics and manufacturing wastes at Station 4 with the relative importance value of the performance metrics. These tables are used as an input for the proposed lean strategies selection methodology for selecting and suggesting proper sets of lean tools for workstation 4 at the QMC production line. In the next stage, the cost and time associated with lean strategies implementation is calculated.

3.5.8 Resource requirements for implementing lean initiatives

In this section, four anticipated cost units and for anticipated time units for each lean tool are estimated. The level of lean implementation is divided into three groups: simple moderate and comprehensive, which relates to the level of lean adoption for improving the current manufacturing system. For the purpose of this research low, medium and high are considered associated with the levels of complexity of relationships. The lean initiatives implementation cost can be assigned as no cost, low cost, moderate cost or high cost. A similar approach can be used to estimate the time units for lean implementation (please refer to Appendix A for more information).

In Table 3.5, the cost and time units of each lean strategy is presented. These units are estimated from the maximum 10 units.

Table 3.4: Correlation matrix between lean techniques, performance metrics and wastes with relative importance weight of each metric and waste

Knowledge disconnection	Raw material inventories	WIP	Failure time	Over processing	Final goods inventory	Unnecessary transportation	defects	Setup time	Unnecessary movements	Manufacturing wastes / Performance metrics	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	Number of work related injuries	Supplier responsiveness	On-time Delivery
5	4	4	6	7	5	7	8	7	9	Relative importance weights	9	7	8	9	6	5	8	5	6	4	4	5
0	0	0	0	0	0	0	0	0	1	5S	0	0	1	0	0	0	0	0	0	1	0	1
0	0	0	1	0	0	0	0	0	0	TPM	0	0	0	0	0	0	1	0	0	0	0	0
0	1	1	0	0	1	0	0	0	0	JIT	1	1	1	0	1	0	0	0	0	0	0	1
0	0	0	0	0	0	0	1	0	0	TQM	0	0	0	0	0	0	0	1	1	0	0	0
0	1	1	0	0	1	0	0	0	0	Kanban	0	1	0	1	0	0	0	0	0	0	0	1
0	0	0	0	0	1	0	0	0	0	Production smoothing	0	0	0	0	0	0	0	1	0	0	0	0
0	0	0	0	1	0	0	0	0	0	Standard work process	1	0	0	0	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	0	0	Visual management	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	1	Cellular manufacturing	0	0	1	0	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	SMED	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	Safety improvement system	0	0	0	0	0	0	0	0	0	1	0	0
1	0	0	0	0	0	0	0	0	0	Information flow management system	0	0	0	0	0	0	0	0	0	0	1	0

Table 3.5: Lean strategies cost and time units

Lean tools	Operating costs	Amortisation cost	Variable cost	Risk cost	Planning time	Training time	Development time	Validation time
5S	3	3	2	3	4	2	3	3
Total Productive Maintenance	9	7	3	2	9	3	4	4
Just-In-Time (JIT)	8	4	3	7	6	5	8	4
Total Quality Management	8	4	4	3	5	4	6	4
Pull/Kanban system	7	7	4	3	6	6	5	5
Production Smoothing	6	2	2	5	4	5	4	2
Standard Work Process	5	1	2	6	3	4	2	3
Visual Management	6	6	3	3	6	6	5	3
Cellular Manufacturing	8	5	2	4	8	7	4	4
Single Minute Exchange of Die (SMED)	6	4	2	5	6	6	4	4
Safety Improvement Program	7	3	2	2	4	3	4	2
Information Flow Management Systems	5	9	3	1	9	8	6	4

In this research it is assumed that if implementing a lean strategy addresses more than one manufacturing waste or performance metric, no extra cost and time is added to the project. In this example, JIT has a high correlation with more than one performance metric. The impacts of JIT on identified performance metrics are as below:

	Cost per part	Total Inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall Equipment efficiency	Rework rate	Customer satisfaction	Number of work-related injuries	Supplier responsiveness	On-time delivery
JIT	1	1	1	0	1	0	0	0	0	0	0	1

Therefore, where JIT, for instance, is selected for implementation the time and cost of implementation using Equation 3.4 to Equation 3.18 are as below:

	Operating costs	Amortisation cost	Variable cost	Risk cost	Planning time	Training time	Development time	Validation time
JIT	8	4	3	7	6	5	8	4

In addition, the budget and time allocation constraints of the HMC company are presented in Table 3.6. The cost and time constraints of the company are presented as units due to confidentiality matters. However, these data can be presented using different units of measurement such as hours for time constraints and dollars for budget constraints.

3.6 Discussion

3.6.1 Suggested lean initiatives based on the proposed methodology

The lean strategies selection model suggests the most appropriate lean strategies considering the relationships between lean tools and performance metrics and lean tools and manufacturing wastes within the manufacturer's budget and time constraints. Figure 3.4 shows the framework for finding the optimum solution for selecting lean strategies. The Excel spreadsheet was used to prepare the input for the model and store the data required in the lean strategies selection method. The database for this model includes the list of lean strategies, identified manufacturing wastes, performance metrics, the correlation matrix between lean tools, performance metrics and wastes. It also includes the guidelines for estimating the cost and time index of lean implementation as well as the perceived value index because identification of these data depends on the selected process.

In this chapter, a MATLAB program was developed to solve the equations mentioned earlier and to suggest the optimum solutions. In this research study, we assumed that the effect of forced change is zero. This means that the implementation of one lean strategy does not influence the implementation of another lean strategy. Therefore, the interdependencies of lean strategies are not considered in this research study.

Table 3.6: Company time and budget limitations for lean implementation

Cost and time components	Constraint unit
Operating cost	50
Amortisation cost	40
Variable cost	45
Risk cost	50
Planning time	55
Training time	45
Development time	35
Validation time	50

After preparing all the inputs required for the model, the MATLAB program generated 867 different scenarios of selected performance metrics and manufacturing wastes and relevant lean strategies. All these scenarios are within the budget and time constraints of the company. The results of these scenarios are provided in Appendix C and Appendix D. The output of the model and the analysis of these results show that manufacturers can choose from 867 different options for their identified performance metrics, manufacturing wastes and lean tools to improve their critical metrics and wastes within their budgetary constraints and allocated time.

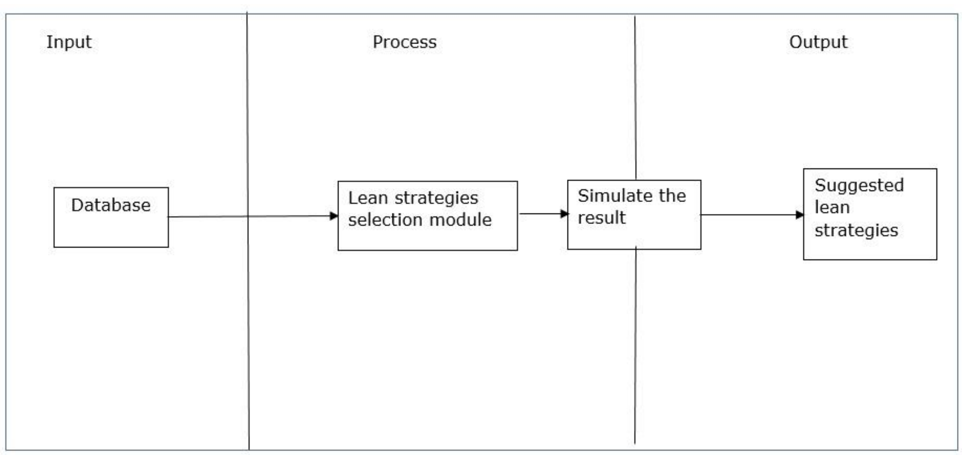

Figure 3.4: Finding the optimum solution framework.

According to the results, the highest perceived value of improving performance metrics and reducing manufacturing wastes is 94. This was calculated by adding the perceived value of reducing wastes (47) to the perceived value of improving performance metrics (47). In contrast, the minimum perceived value of lean implementation for this company is 6 (Appendix C and Appendix D). Table 3.7 shows the most appropriate combination of lean tools and identified performance metrics and manufacturing wastes that meet the resource limitations of the selected modular construction company. Based on the results of the MATLAB program, the manufacturer can select at least one and at most seven performance metrics out of the twelve identified metrics. They can also choose at least one and at most eight manufacturing wastes out of ten identified wastes. The results show that the selected performance metrics are cost per part, transportation cost, setup time, manufacturing lead time, overall equipment efficiency, rework rate and customer satisfaction. The target manufacturing wastes are unnecessary movements, setup time, unnecessary transportation, final products inventory, over processing, Failure time, WIP and raw material inventories. In this respect, the suggested lean techniques are 5S, TPM, JIT, Pull/Kanban system, Production Smoothing, Standard Work Process, Cellular Manufacturing and SMED. This result aims to maximise the perceived value of lean implementation for improving performance metrics and reducing the company's manufacturing wastes.

According to Table 3.7, JIT impacts on more performance metrics and manufacturing wastes compared to other selected lean strategies. It can help manufacturers by improving cost per part, total inventory cost, transportation cost, manufacturing lead time and on-time delivery performance metrics as well as eliminating final products, WIP and raw materials inventories. The second beneficial lean strategy among the set of selected tools is the Kanban system. This addresses three wastes: final goods inventory, WIP and raw materials inventory, as well as three performance metrics: total inventory cost, setup time and on-time delivery. After this lean strategy, Cellular Manufacturing has the highest benefit by addressing two manufacturing wastes (unnecessary movements and transportations) and three performance metrics (transportation cost, manufacturing lead time and labour productivity). 5S is the next most appropriate lean strategy, which improves four performance metrics and reduces one manufacturing waste. Finally, Standard

Work Process can improve efficiency in the production process by reducing over processing waste and enhancing cost per part and customer satisfaction performance metrics.

In the QMC manufacturing line, unnecessary movement is one of the critical manufacturing wastes identified by the decision makers and top managers. Therefore, application of the 5S principle can help the manufacturer reduce this waste alongside implementation of Cellular Manufacturing. This lean initiative also has a positive influence on the transportation cost metric. SMED is one of the lean initiatives with a primary focus on setup time reduction. Therefore, one of the selected lean strategies is SMED to reduce the setup and changeover time. In addition, overall equipment efficiency is one of the performance metrics that is related to the TPM lean initiative. This lean strategy is also valuable in reducing failure time in the manufacturing firm. Finally, Production Smoothing can reduce finished product inventories as well as rework rate. Therefore, this research study suggests implementing the selected lean strategies in this sequence:

Table 3.7: The best combination of lean strategies, performance metrics and manufacturing wastes

Total perceived value	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall Equipment Efficiency	Rework rate	Customer satisfaction	Number of work-related injuries	Supplier responsiveness	On-time delivery			Unnecessary movements	Setup time	Defects	Unnecessary transportation	Final goods inventory	Over processing	Failure time	WIP	Raw material inventory	Knowledge disconnection	Total perceived value
	4	5	9	9	7	5	8	5	5	3	4	7	Perceived value		9	7	5	9	5	7	5	4	4	3	
	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}	M_{11}	M_{12}	Selected metrics	Selected wastes	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	
47	1	0	1	1	1	0	1	1	1	0	0	0			1	1	0	1	1	1	1	1	1	0	47
1	0	0	1	0	0	1	0	0	0	1	0	1	**5S**		1	0	0	0	0	0	0	0	0	0	1
1	0	0	0	0	0	0	1	0	0	0	0	0	Total Productive Maintenance		0	0	0	0	0	0	1	0	0	0	1
1	1	1	1	0	1	0	0	0	0	0	0	1	**JIT**		0	0	0	0	1	0	0	1	1	0	1
1	0	0	0	0	0	0	0	1	1	0	0	0	**Total Quality Management**		0	0	1	0	0	0	0	0	0	0	0
1	0	1	0	1	0	0	0	0	0	0	0	1	**Pull/Kanban system**		0	0	0	0	1	0	0	1	1	0	1
1	0	0	0	0	0	0	0	1	0	0	0	0	**Production Smoothing**		0	0	0	0	1	0	0	0	0	0	1
1	1	0	0	0	0	0	0	0	1	0	0	0	**Standard Work Process**		0	0	0	0	0	1	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	Visual Management		0	0	0	0	0	0	0	0	0	0	0
1	0	0	1	0	1	1	0	0	0	0	0	0	**Cellular Manufacturing**		1	0	0	1	0	0	0	0	0	0	1
1	0	0	0	1	0	0	0	0	0	0	0	0	**Single Minute Exchange of Die**		0	1	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	1	0	0	Safety Improvement Program		0	0	0	0	0	0	1	0	0	0	1
1	0	1	0	0	1	0	0	0	0	0	1	0	Information Flow Management Systems		0	0	0	0	0	0	0	0	0	1	0

The calculation of the total cost and time associated with lean implementation is presented in Section 0. Table 3.8 demonstrates the actual budget and time required for adopting the suggested lean techniques.

Table 3.8: Comparison of actual lean implementation cost and time with resource constraints

Cost and time components	budget and time maximum limit	Actual cost and time
Operating cost	50	50
Amortisation cost	40	33
Variable cost	45	20
Risk cost	50	35
Planning time	55	46
Training time	45	38
Development time	35	34
Validation time	50	39

The next section describes the sensitivity analysis to determine the effect of the dynamic situation in the manufacturing organisation on the result of the lean strategies selection method.

3.7 Validation of the developed lean initiative selection methodology

Every manufacturing organisation is performing in a dynamic situation due to changes in the internal performance or in the external environment of the organisation. Therefore, it is always challenging for the top management team and decision makers to consider these kinds of fluctuations when selecting any improvement programs in the production line. For instance, as a result of implementing previous improvement programs, the performance situation could be changed. Also, the amount of resources allocated by decision makers for adopting an innovative program in the company may change based on their requirements over time. Therefore, the developed lean strategies selection approach facilitates the change in the decision-making process by changing the input of the model. These changes can be an alteration in cost and time constraints and the relative importance value of the performance metrics and manufacturing wastes.

In the previous section, transportation cost and setup time were the critical performance metrics. Unnecessary movements and transportation were the critical manufacturing wastes identified by the managers. The problem was solved by considering the above input. However, in this section, it is assumed that the situation of the company has changed and the management team has decided that total inventory cost is the most critical performance indicator and WIP and raw materials inventory are the most critical manufacturing wastes. Moreover, managers decided to allocate a different amount of cost and time to implement the new set of lean strategies. Thus, the new problem defined is that the program will solve based on the new critical wastes and metrics as well as budget and time allocation.

The result obtained from the new problem is provided in Table 3.9, which illustrates the best combination of lean tools, metrics and wastes. The set of appropriate lean strategies that address both manufacturing wastes and performance metrics is JIT, TQM, Kanban system, Standard Work Process, Cellular Manufacturing and Information Flow Management System.

The maximum value obtained by implementing the best combination of lean tools is 79 and the minimum is 6 (see Appendix E and Appendix F). The comparison of the new budget and period limitations with actual budget and time required for implementing appropriate lean initiatives is provided in Table 3.10. The iteration results of the MATLAB program are provided in Appendix E and Appendix F. The developed model suggests 664 different combinations of lean strategies, performance metrics and wastes, which can help managers to choose and suggest the best set of lean tools for implementation to improve critical performance metrics and reduce their critical manufacturing wastes.

Table 3.9: The best combinations of lean strategies, performance metrics and manufacturing wastes in dynamic situation

Total perceived value	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall Equipment Efficiency	Rework rate	Customer satisfaction	Number of work-related injuries	Supplier responsiveness	On-time delivery		Unnecessary movements	Setup time	Defects	Unnecessary transportation	Final goods inventory	Over processing	Failure time	WIP	Raw material inventory	Knowledge disconnection	Total perceived value
	4	9	4	3	7	5	8	5	5	3	4	7	Perceived value	4	7	5	4	5	7	5	9	9	3	
	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}	M_{11}	M_{12}	Selected metrics / Selected wastes	W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	
38	1	1	0	0	1	0	1	1	1	0	0	0		1	0	1	1	0	1	0	1	1	1	41
1	0	0	1	0	0	1	0	0	0	1	0	1	5S	1	0	0	0	0	0	0	0	0	0	1
1	0	0	0	0	0	0	1	0	0	0	0	0	Total Productive Maintenance	0	0	0	0	0	0	1	0	0	0	1
1	1	1	1	0	1	0	0	0	0	0	0	1	**JIT**	0	0	0	0	1	0	0	1	1	0	1
1	0	0	0	0	0	0	0	1	1	0	0	0	**Total Quality Management**	0	0	1	0	0	0	0	0	0	0	0
1	0	1	0	1	0	0	0	0	0	0	0	1	**Pull/Kanban system**	0	0	0	0	1	0	0	1	1	0	1
1	0	0	0	0	0	0	0	1	0	0	0	0	Production Smoothing	0	0	0	0	1	0	0	0	0	0	1
1	1	0	0	0	0	0	0	0	1	0	0	0	**Standard work process**	0	0	0	0	0	1	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	Visual Management	0	0	0	0	0	0	0	0	0	0	0
1	0	0	1	0	1	1	0	0	0	0	0	0	**Cellular Manufacturing**	1	0	0	1	0	0	0	0	0	0	1
1	0	0	0	1	0	0	0	0	0	0	0	0	Single Minute Exchange of Die	0	1	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	1	0	0	Safety Improvement Program	0	0	0	0	0	0	1	0	0	0	1
1	0	1	0	0	1	0	0	0	0	0	1	0	**Information Flow Management Systems**	0	0	0	0	0	0	0	0	0	1	0

Table 3.10: Actual cost and time with cost and time constraints in a dynamic situation

	Primary constraints	Actual cost and time	Readjusted cost and time constraints	New actual cost and time
Operating cost	50	50	40	41
Amortization cost	40	33	45	30
Variable cost	45	20	35	18
Risk cost	50	35	45	24
Planning time	55	46	50	37
Training time	45	38	50	34
Development time	35	34	35	31
Validation time	50	39	40	24

Therefore, this section shows that the selection of lean strategies is related to the relative importance weightings of performance metrics and manufacturing wastes as well as the amount of resource constraints. This means that any alterations in the input of the developed methodology can result in generating different combinations of lean strategies, performance metrics and manufacturing wastes. As a result, it emphasises identification of relevant performance metrics and manufacturing wastes for the manufacturing process and resource constraints of manufacturers.

3.8 Conclusion

Selecting the best set of lean strategies for implementation to improve the selected areas of the manufacturing process and address the manufacturing problems is always a significant challenge for managers and decision makers. Therefore, it is essential to achieve the maximum benefits of lean philosophy by adopting a proper set of lean tools within the budgetary and time limitations of the organisation. The significant contribution of this research study is the development of the mathematical methodology that considers the correlation of lean strategies with performance metrics and manufacturing wastes simultaneously. The proposed decision-making model is a novel methodology for suggesting the best set of lean techniques that maximise the manufacturer’s perceived effectiveness value of improving performance metrics and reducing manufacturing wastes within the allocated time and budgetary constraints. In this model, it is essential to identify critical performance metrics from different categories and critical manufacturing wastes to increase the accuracy of the lean strategies selection model within its limitations.

The result from the proposed methodology in this chapter is more accurate compared to previous methods found in the literature. The developed methodology suggests more accurate sequence of lean techniques for implementation that not only impact the critical production wastes but also significantly improve identified performance metrics. Therefore, implementation of the suggested lean tools helps manufacturers perform efficiently in the competitive market while reducing their manufacturing wastes. The developed methodology in this research clearly identify which lean tools will directly affect which performance measures.

A real-life case study in the modular construction industry is used to validate the developed methodology. The step-by-step method used to validate the selection model is explained. The proposed decision-making methodology and model is also used in a changing situation of a manufacturing process to assist decision makers in a special situation. Therefore, the major contributions are:

- Development of lean strategies, performance metrics and production wastes correlation matrices as an initial decision-making guideline, illustrating the appropriateness of the lean strategies for improving performance metrics and addressing manufacturing wastes.
- A multi-objective methodology that reaches the maximum level of the perceived value of improving performance metrics while reducing manufacturing wastes.
- A multi-objective methodology that suggest a more accurate sequence of lean tools for implementation that improves identified performance metrics while eliminating production wastes.
- A methodology that illustrates the effect of lean initiatives directly on performance metrics beside manufacturing wastes.

Chapter 4: The weighted leanness measurement methodology and relevant research methodology

A new methodology was proposed through this research to measure the overall leanness of a manufacturing organisation considering the interdependent relationships between identified performance metrics. Leanness can be defined as the degree of adoption and implementation of lean manufacturing principles. Therefore, the aim of leanness assessment approaches is to quantify and measure the leanness level (Soriano-Meier & Forrester 2002; Papadopoulou & Özbayrak 2005; Wong et al. 2012). In this chapter, a methodology is developed to be used to measure the overall leanness of the organisation while considering the interrelationships between different lean performance metrics, and hence, providing a meaningful integrated lean index. The next section explains the fuzzy-based Analytic Network Process (ANP) approach used to develop other leanness assessment models and allocate relative importance weightings to the performance metrics. Finally, an industrial case study is presented to validate the proposed model.

4.1 Research approach for measuring the leanness score based on unequal relationships between performance metrics

The developmental phases of an overall leanness measurement model for manufacturing organisations, which considers the interrelationship between different performance metrics is presented in this section. In order to achieve this research objective, the following step should be fulfilled:

- Developing a weighted fuzzy-based leanness evaluation methodology

To meet the second objective of this research project, a weighted methodology using fuzzy set theory for performance indicators will be developed to improve the previous models and to obtain more accurate results from the overall leanness measurement process. In the proposed model, the overall leanness score of the organisation will be measured by considering the interrelationships between performance indicators (both qualitative and quantitative metrics) as variability in one performance metrics could cause changes in other performance variables. This process faces enormous uncertainties; therefore, fuzzy set logic will be used to deal with these ambiguities. The details of the proposed methodology for providing the overall index for the leanness level of organisation is provided.

4.1.1 Description of lean measures and performance metrics

As mentioned earlier, leanness evaluation refers to the tools used to measure the current state of the manufacturing company and provide a direction from the existing situation to the future state (Ramesh & Kodali 2012; Wong et al. 2012). In this regard, researchers need to identify and understand performance measures to track the leanness level. Cost, on-time delivery and quality were introduced as performance measures (Agarwal et al. 2006). Allen et al. (2001) included safety and productivity on that list. In addition, Dennis and Shook (2007) identified six main performance measures for measuring an organisation's leanness level: quality, productivity, safety, cost, delivery, environment and morale. However, to evaluate different aspects of each performance measure, it is required to define a set of performance metrics for each measure's category.

Performance metrics can be expressed in linguistic or numerical terms. For instance, Daum and Bretscher (2004) defined linguistic (qualitative) metrics to reflect the stakeholders' opinion in measuring the same performance metric. Other researchers defined individual metrics, Manufacturing Cycle Efficiency (MCE) and Value-Added Efficiency (VAE) to measure the leanness score quantitatively (Fogarty 1992; Levinson & Rerick 2002). In another research study conducted by Katayama & Bennett 1999, quality and productivity were considered to measure the leanness level. Recently, researchers attempted to integrate a group of performance metrics to measure the integrated leanness score of the manufacturing organisation. In this regard, Detty and Yingling (2000) measured the overall leanness by grouping quality, productivity and cost, and Amin (2012) focused on several performance metrics from different categories to measure the overall leanness score of the organisation using fuzzy logic.

However, previous researchers were not successful in developing an integrated leanness measurement methodology that considers the interdependent relationship between different performance indicators. For a meaningful, integrated leanness index, the interrelationships of these metrics need to be investigated. For instance, increasing quality through frequent inspections or consuming more resources can increase the operating cost of the manufacturing process. Also, extending the manufacturing lead time, and consequently, on-time delivery requires additional production processes that can increase operational costs. Therefore, cost may have an impact on quality and on-time delivery that needs to be considered when assessing the leanness score of the organisation.

According to Inanjai and Farris (2009), cost, quality, performance, delivery time, flexibility and innovation are six primary outputs of every manufacturing firm. Cost consists of material, labour, resources and overhead costs used to produce a product. Quality is the ability of the final products to meet the requirements of the customers. Performance refers to the product specifications that cannot be seen in other products. Delivery time is the period of time from taking the order from the customer to delivery of the finished product to the consumer. Flexibility refers to the ability of the organisation to extend their production volume, and innovation is the ability of the organisation to introduce new products to the market.

For the purpose of this research a set of lean performance metrics is determined through a comprehensive literature review to assess the performance of the production process. The list of widely used lean performance metrics is provided in Appendix B. The main focus of this research is to develop a weighted leanness measurement methodology that considers the interdependent relationships between the performance indicators and provide an integrated lean index. For this purpose, a fuzzy-based Analytic Network Process (ANP) approach was used to determine the degree of interdependence between performance measures and performance metrics as well as the inter-dependence between them. Moreover, Cross Industry Standard Process (CRISP) evaluation may not be adequate for capturing the importance assessment for performance measures and metrics. Therefore, a fuzzy set concept is used to deal with uncertainties and ambiguities in this approach. The proposed weighting method provides a more accurate approach to measure the leanness level of the manufacturing firm.

4.2 Theoretical background

According to the definition of leanness, the leanness assessment refers to the tools and techniques used to measure the current performance and the leanness level of the manufacturing organisation as well as the efficiency of the existing operations (Muthiah & Huang 2006; Wong et al. 2012). In this regard, several research studies developed methodologies to measure the leanness level of the organisation and track improvements achieved by the implementation of lean initiatives. Some of the methodologies found in the literature introduced various performance metrics that reflect specific aspects of the manufacturing process, while others selected and used a group of performance metrics to measure the total score of organisation leanness. However, to the best of our knowledge, the interdependent relationships between different lean performance metrics (both qualitative and quantitative) has not been used to assess the integrated leanness score. Therefore, lean practitioners know how to measure the overall leanness score and how to improve it, but they do not have the knowledge to consider the interrelationships between lean performance metrics to measure and evaluate the integrated leanness score.

To develop an effective leanness assessment model, we need to understand how different lean performance metrics from different performance measure categories interrelate with each other. For instance, producing high-quality products increases the manufacturing cost and the amount of resources required. Also, extending the customer delivery time requires additional operating costs in the organisation. In this regard, a weighted leanness assessment model should be developed to consider the interrelationships between performance indicators for assessing the overall leanness index of the organisation. This research proposes the leanness assessment model that considers these interrelationships by using fuzzy logic to consider uncertainties and impreciseness of production data (Zadeh 1965). The main focus of this research is to develop an integrated leanness index that considers the interdependent relationships between lean performance measures and performance metrics.

This research tracks the following primary stages to develop the weighted fuzzy-based leanness assessment model:

- **Identifying lean performance measures and performance metrics:** selecting an appropriate set of lean performance metrics associated with the production process.
- **Establishing interdependent relationships between lean performance metrics:** determining the interdependent relationships between different qualitative and quantitative performance metrics to prioritise these metrics based on the manufacturer's requirements.
- **Measuring the overall leanness of the organisation:** measuring the integrated leanness value that considers the interrelationships between lean performance indicators.

4.3 Basic concept of fuzzy set theory and its triangular numbers

Fuzzy set theory was developed by Zadeh (1965). The main purpose of this theory was to quantify natural language due to ambiguity and vagueness of words. It is believed that this theory is an extension of the traditional CRISP set, in which each individual is either a member or non-member of the CRISP set. Therefore, for a given CRISP set A, the value of the $\mu_A(x)$ function assigned to each x is:

$$\mu_A(x) = f(x) = \begin{cases} 1, & x \in X \\ 0, & x \notin X \end{cases}$$ Equation 4.1

In this function, the value allocated to each element is 1 or 0. This can be indicated by:

$$\mu_A: X \rightarrow \{0, 1\}$$ Equation 4.2

This function can be generalised by assigning values to universal set elements and is called the membership degree of these elements in the set. A larger value represents a higher membership degree. Therefore, this function can be indicated by:

$$\mu_A: X \rightarrow [0,1]$$ Equation 4.3

A fuzzy set $\tilde{a}$ in universe of discourse X is specified by $\mu_A(x)$ as a membership function. Each element x in X is mapped by a membership function to a real number in the interval [0,1]. The function value of $\mu_A(x)$ represents the degree of membership of x in a fuzzy set $\tilde{a}$ (Zadeh 1965; Buckley 1985a; Kaufmann & Gupta 1991; Klir & Yuan 1995; Zimmermann 2011).

A triangular fuzzy number is represented as $A = (a_1, a_2, a_3)$. These numbers are very common in practical application due to their simplicity in concept and calculation (Pedrycz 1994; Klir & Yuan 1995; Yeh & Deng 2004). The membership function $\mu_A(x)$ of triangular fuzzy number A is:

$$\mu_A(x) = \begin{cases} 0, & x \leq a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, & a_1 \leq x \leq a_2 \\ \dfrac{a_3 - x}{a_3 - a_2}, & a_2 \leq x \leq a_3 \\ 0 & x \geq a_3 \end{cases} \qquad \text{Equation 4.4}$$

Where $a_1, a_2\ and\ a_3$ are real numbers and $a_1 \leq a_2 \leq a_3$. The value of x at a_2 reaches the highest grade of $\mu_A(x) = 1$ and gives the minimal value of $\mu_A(x) = 0$ at a_1 and a_3; it is the most and the least likely value of the assessment data, respectively. a_1 and a_3 are the upper and lower limits of the evaluation data and reflect the fuzziness of the evaluation data. The narrower the interval $[a_1$ $a_3]$, the lower the fuzziness of the evaluation data.

If we assume that $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$ are two triangular fuzzy numbers, the main operations for these two fuzzy numbers are as follows:

Addition of two triangular fuzzy numbers

$\tilde{a} + \tilde{b} = (a_1 + b_1, a_2 + b_2, a_3 + b_3), \quad a_1 \geq 0, b_1 \geq 0$

Multiplication of two triangular fuzzy numbers

$\tilde{a} \times \tilde{b} = (a_1 \times b_1, a_2 \times b_2, a_3 \times b_3), \quad a_1 \geq 0, b_1 \geq 0$

Subtraction of two triangular fuzzy numbers

$\tilde{a} - \tilde{b} = (a_1 - b_1, a_2 - b_2, a_3 - b_3), \quad a_1 \geq 0, b_1 \geq 0$

Division of two triangular fuzzy numbers

$\tilde{a} \div \tilde{b}$ =(min (a_1/b_1 , a_1/b_3 , a_3/b_1 , a_3/b_3), a_2/b_2, max (a_1/b_1 , a_1/b_3 , a_3/b_1 , a_3/b_3)),

$a_1 \geq 0, b_1 \geq 0$

Inverse of a triangular fuzzy number

$\tilde{a}^{-1}$= ($1/a_3$, $1/a_2$, $1/a_1$), $\quad a_1 \geq 0$

Symmetric image

$\widetilde{-a} = (-a_3, -a_2, -a_1), \quad a_1 \geq 0$

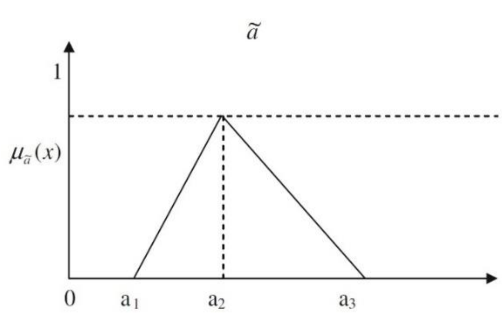

Figure 4.1: Sample of a triangular fuzzy number.

4.4 Weighted leanness measurement methodology using fuzzy logic

In this section, a weighted leanness measurement methodology using fuzzy logic, which considers the interrelationships between lean performance measures and performance metrics in the production process is presented. The fuzzy membership function of each performance metric is evaluated by fuzzy set theory and linguistic terms (both quantitative and qualitative metrics). In this section, triangular fuzzy numbers are used due to their simplicity in computation. Then, a fuzzy-ANP approach is used to establish the interrelationships between lean performance measures and performance metrics and assign the relative importance weightings to these performance metrics. Finally, the overall leanness level of the manufacturing process is measured by considering the importance weightings of the metrics. The main steps of the proposed leanness assessment model are as below:

Step 1	Determine fuzzy numbers using linguistic terms for both qualitative and quantitative measures
Step 2	Determine lean ranges of lean performance metrics
Step 3	The uniformity membership function to fuzzify multiple membership
Step 4	Determine triangular fuzzy scale for the importance weightings of measures and metrics
Step5	Construct the relationship network between performance measures and metrics using the ANP method
Step 6	Calculate the relative importance weightings for each pairwise comparison matrix
Step 7	Computate the overall leanness considering the relative importance weightings for each performance metric

4.4.1 Converting linguistic and numerical data into fuzzy numbers for each performance metric

In this step, each metric's values are converted into triangular fuzzy numbers. First, the values of each performance metric are collected from the manufacturing organisation. Let $s_i, i = 1, 2, \dots, t$ be a different situation in the manufacturing organisation (for example, before and after lean implementation), lp_j, $j = 1, 2, \dots, m$ are the lean performance measures and pm_k, $k = 1, 2, \dots, n$ are the different performance metrics identified for the production process. For those performance metrics that indicate benefit, higher values of pm_k are better; for performance metrics which indicate cost, lower values of pm_k are better. Converting the raw values of performance metrics to fuzzy triangular numbers starts with collecting the numerical values in different observations. Thus, N observations for each performance metric pm_k under situation s_i and performance category lp_j can be expressed as $x_{ijkl} = x(s_i, lp_j, pm_k, l), l = (1, 2, \dots, N)$. The next section presents the algorithm for converting raw data to the TFN proposed by Hong and Lee (1996). This method is applied to lean manufacturing by Amin (2012). However, the above mentioned authors assumed equal interrelationships between lean performance metrics in their leanness assessment model. The following steps should be applied to convert raw data into triangular fuzzy numbers (Amin, 2012):

Steps for converting raw data into fuzzy numbers	Equation	Equation number
Step 1: Find differences between consecutive data	$d_l = x_{ijkl} - x_{ijk(l-1)}$	Equation 4.5
Step 2: Assign the similarity value between adjacent values	$S_{ijkl} = \begin{cases} 1 - \dfrac{d_l}{C \times \sigma}, & d_l < C \times \sigma \\ 0, & otherwise \end{cases}$ (*C* is the control parameter)	Equation 4.6
	$\sigma = \sqrt{\dfrac{1}{N-1} \sum_{1}^{N} (x_i - \bar{x})^2}$	Equation 4.7
Step 3: Define fuzzy linguistic terms and relevant membership function	$b_{ijkz} = \dfrac{x_{ijk1} \times S_{ijk2} + \sum_{l=2}^{N-1} x_{ijkl} \times w_{ijkl} + x_{ijkN} \times S_{ijkN}}{S_{ijk2} + \sum_{l=2}^{N-1} w_{ijkl} + S_{ijkN}}$ $w_{ijkl} = \dfrac{S_{ijkl} + S_{ijk(l+1)}}{2}$	Equation 4.8
Step 4: Calculating the membership values of a_{ijkz} and c_{ijkz}	$a_{ijkz} = b_{ijkz} - \dfrac{b_{ijkz} - x_{ijkl}}{1 - \mu(x_{ijkl})}$	Equation 4.9
	$c_{ijkz} = b_{ijkz} + \dfrac{x_{ijkl} - b_{ijkz}}{1 - \mu(x_{ijkl})}$	Equation 4.10
	$(x_{ijkl}) = \min(S_{ijkl}, S_{ijk(l+1)}, \dots)$	Equation 4.11

Step 5: The membership function of each performance metric	$F_{ijkz} = (a_{ijkz}, b_{ijkz}, c_{ijkz})$	Equation 4.12
Ideal lean range: positive behaviour of variables (pm_k)	$L_{ijkz}x = a_{ijkz} - b_{ijkz}$	Equation 4.13
Ideal lean range: negative behaviour of variables (pm_k)	$L_{ijkz}y = c_{ijkz} - b_{ijkz}$	Equation 4.14
Optimum lean range: positive behaviour of variables (pm_k)	$L_{ijkz}x = a_{ijkz} - R$	Equation 4.15
	$L_{ijkz}x = a_{ijkz} - G$	Equation 4.16
Optimum lean range: negative behaviour of variables (pm_k)	$L_{ijkz}y = c_{ijkz} - R$	Equation 4.17
	$L_{ijkz}y = c_{ijkz} - G$	Equation 4.18

Figure 4.2 and Figure 4.3 illustrate the relationship between the ideal and optimum leanness for the cost and benefit performance metrics goals. In these figures, the x axis shows the performance metrics (cost and benefit) and the y axis shows the corresponding membership values (leanness value).

In an ideal situation, the manufacturing system operates without any production wastes and non-value-adding activities. Therefore, in an ideal manufacturing system a_{ijkz}, b, c_{ijkz} is the triangular fuzzy number for the performance metrics that have a maximum membership value or ideal value (i.e. 1) at point b. However, in a real production situation, some manufacturing wastes exist and the RR' and GG' shows its triangular fuzzy numbers.

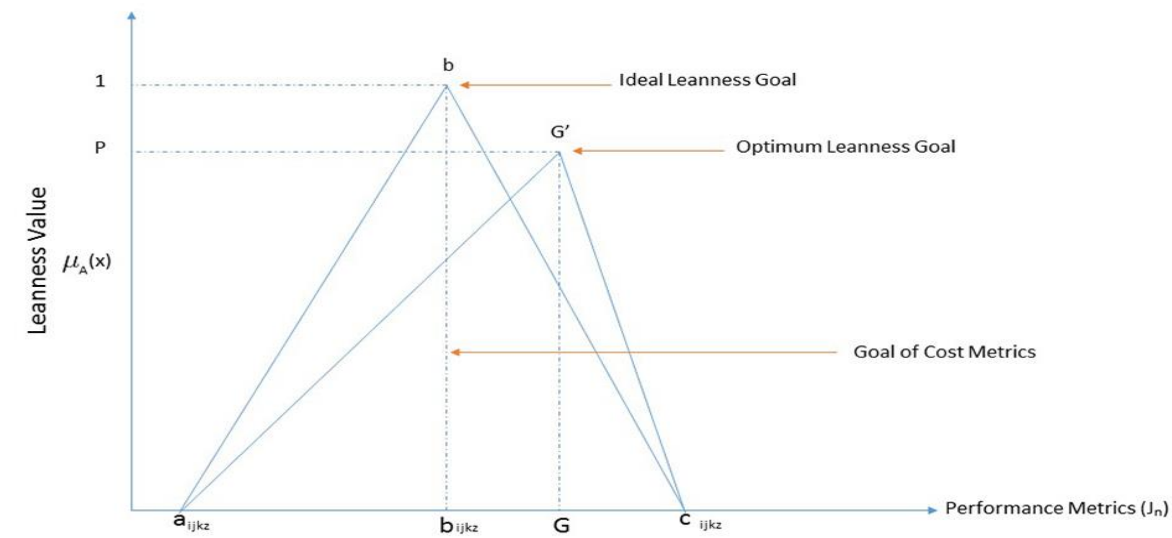

Figure 4.2: Comparison of ideal and optimum leanness points for negative metrics.

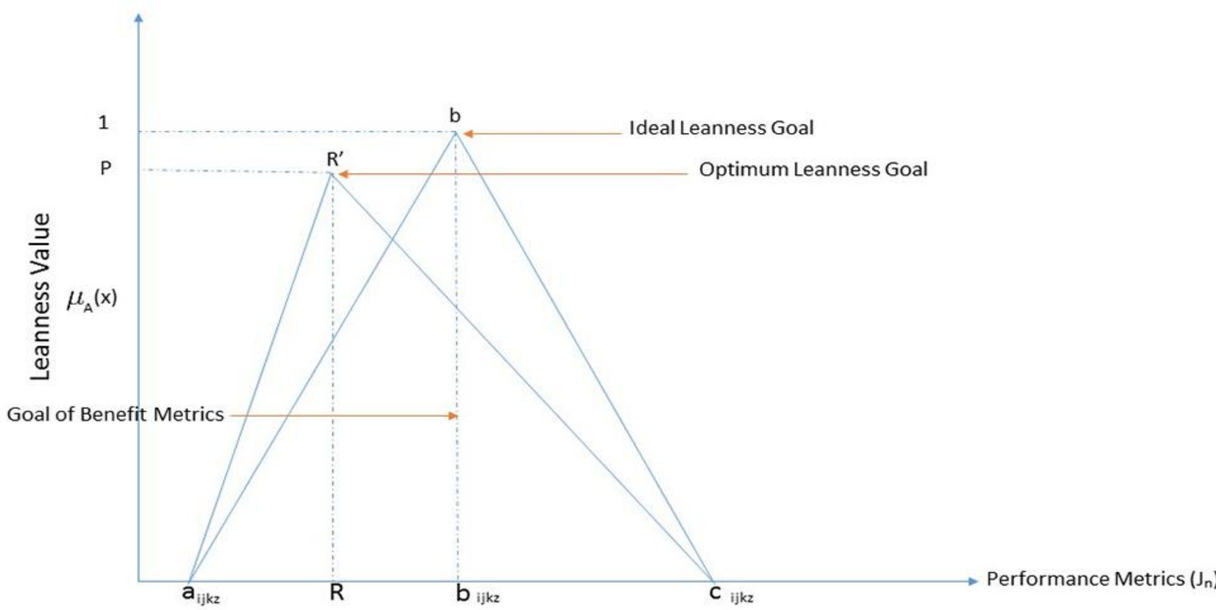

Figure 4.3: Comparison of ideal and optimum leanness points for positive metrics.

Therefore, the target of improvement for both types of performance metrics is to achieve the maximum membership value, i.e. b_{ijkz}. This is the target point for any manufacturer: that both cost and benefit metrics can achieve 1 or 100%. Therefore, the ideal lean range for positive behaviour lean performance metrics, pm_k (variables required to improve by increasing the value of their performance), is from point a_{ijkz} to point b_{ijkz} . Similarly, for negative performance metrics it is from point c_{ijkz} to b_{ijkz}. These lean ranges for adopting lean tools are taken to achieve the ideal leanness index (Chang et al. 2006; Amin 2012).

However, it is not possible to achieve the ideal leanness (100% leanness) because the perfect production system without any wastes does not exist in reality. Therefore, the realistic lean goal for lean strategies implementation is to minimise wastes to improve the performance and achieve a greater leanness value. Figure 4.2 and Figure 4.3 present two triangular fuzzy numbers for realistic leanness values, which are (a_{ijkz}, R, c_{ijkz}) and (a_{ijkz}, G, c_{ijkz}). In a realistic situation, the value of metric variables (the membership function value, $\mu(x)$) is decreased from 1 to P (point R' or G'). This is mainly due to the existence of manufacturing wastes in the organisation. Thus, P is defined as a realistic leanness value for managers (Chang et al. 2006; Wang et al. 2009; Amin 2012).

Performance metrics	Uniformity triangular membership function	
positive behaviour of performance metrics $\mathbf{pm_k}$	$\mu_{ijkl} = \frac{x_{ijkl} - x_{ijkl}^{min}}{x_{ijkl}^{max} - x_{ijkl}^{min}}$	Equation 4.19
negative behaviour of performance metrics $\mathbf{pm_k}$	$\mu_{ijkl} = \frac{x_{ijkl}^{max} - x_{ijkl}}{x_{ijkl}^{max} - x_{ijkl}^{min}}$	Equation 4.20
	$x_{ijkl}^{max} = \max_{l=1,\dots,N} x_{ijkl}$	Equation 4.21
	$x_{ijkl}^{min} = \min_{l=1,\dots,N} x_{ijkl}$	Equation 4.22

As can be seen from Figure 4.2 and Figure 4.3, the same membership function value (the *y* axis) is valid for multiple values of a variable (the *x* axis). Therefore, to avoid generating the same membership function value for different variables, the uniform triangular membership function was developed by Chang et al. (2006) and Wang et al. (2009). Based on Equation 4.19 and Equation 4.20, each value in the *x* axis has its own membership value in the *y* axis. Figure 4.14 illustrates the uniformity conversion of positive and negative variables for the selected performance metrics in the real life-case study used in this research.

4.4.2 Correlation coefficient values of the performance metrics

To develop a meaningful overall leanness index, it is essential to recognize how lean performance metrics are interrelated. Naturally, these interrelationships are inseparable; for instance, quality and on-time delivery both have influences on cost measures. However, these interrelationships become more complex during lean applications throughout the company. In addition, conflicts of interest and incongruent objectives in different sections of the organisation can occur as a result of lean implementation, which can negatively affect the manufacturing performance. Therefore, determining the interrelationships of performance metrics through a common platform, such as a good leanness value, is essential to reduce the impacts of conflicts and measure the integrated leanness level. In this respect, to examine the interrelationships between lean metrics from the perspective of lean focus a common platform should be developed.

In this regard, the author has used MATLAB to illustrate the correlation coefficient of the selected performance metrics. The input data are 10 observations for each performance metrics in different situations and different times (Table 4.5). Thereupon, the correlation coefficient of these metrics are calculated using Equation 4.23 to measure the strength and the direction of a linear relationship between two performance variables. The term correlation is used to signify the association of two different variables. Pearson's correlation coefficient formula (Equation 4.23) is used to measure the degree of the association between two variables. Although the relationship between two variables can be measured using a variety of equations that best fit the nature of the data depending on the association complexity, this thesis considered the relationships which had general trends and assumed linear relationships between lean performance metrics. This means that when one metric value changed in magnitude, the correlated metric followed on average, which can be presented by a straight line drawn through the data points on a scatter plot. Therefore, *r* is a measure of the scatter of the data points around an underlying linear trend. The greater the spread, the lower the value of the correlation coefficient and the lower the degree of straight line association between the metrics. The value of the correlation coefficient varies between -1 and +1 where a positive value indicates that an increase in one variable is linked to an increase in the other, while a negative value indicated that an increase in one variable is linked to a decrease in the other. The correlation coefficient matrix is presented in Table 4.1.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \qquad \text{Equation 4.23}$$

Table 4.1: The correlation coefficient values of the selected performance metrics

	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work related injuries	Supplier responsiveness	On-time Delivery
Cost per part	0	0.585802	-0.53747	-0.02366	-0.01908	0.07736	-0.0137	0.118998	0.021622	0.554936	0.04175	0.469405
Total inventory cost	0	0	-0.54811	0.212754	0.262438	-0.27441	-0.07237	0.661393	-0.2339	0.332849	0.128183	-0.04181
Transportation cost	0	0	0	0.196502	0.054839	0.161199	-0.15926	-0.09079	-0.1398	-0.18078	-0.22562	-0.21217
Setup time	0	0	0	0	0.471868	-0.59816	-0.87107	0.395179	-0.87127	0.425783	-0.70546	-0.67095
Manufacturing lead time	0	0	0	0	0	0.120143	-0.69243	0.450928	-0.66306	0.259956	-0.72356	-0.538
Labour productivity	0	0	0	0	0	0	0.284094	-0.28448	0.396206	-0.05203	0.051962	0.526842
Overall equipment efficiency	0	0	0	0	0	0	0	-0.14048	0.926687	-0.55279	0.838162	0.609496
Rework rate	0	0	0	0	0	0	0	0	-0.30837	0.088731	-0.20614	-0.27651
Customer satisfaction	0	0	0	0	0	0	0	0	0	-0.56541	0.721064	0.643557
No. of work related injuries	0	0	0	0	0	0	0	0	0	0	-0.25653	0.237187
Supplier responsiveness	0	0	0	0	0	0	0	0	0	0	0	0.58574
On-time Delivery	0	0	0	0	0	0	0	0	0	0	0	0

Table 4.1 illustrates the systematic matrix, so only the upper triangular portion of the matrix was studied. A correlation of zero means there is no relationships between the two variables. When the correlation is positive, an increase in one variable leads to increase of the value of other variable. For instance, the correlation coefficient value of supplier responsiveness and on-time delivery is 0.58574, thus as the value of supplier responsiveness increases, the value of on-time delivery increases (the variables move together). When the correlation coefficient value is negative, such as -0.72356 for manufacturing lead time vs. supplier responsiveness, as the value of one variables

increases, the value of the other variable decreases, and vice versa. In addition, a correlation coefficient value greater than 0.8 indicates strong interrelationships among two variables, while a correlation coefficient value less than 0.5 is generally considered as a weak interrelationship (Daya, 2004).

Furthermore, to represent the graphic interrelationship between performance metrics the contour plot was used (Figure 4.4 to Figure 4.13). In these plots the twelve performance metrics are for X and Y variables and the third variable is for the counter levels, which are plotted by using colours to illustrate the magnitude of the interrelationships between two variables.

These plots are indicated for different threshold of the absolute correlation coefficient values. These thresholds are specified based on the requirements and interests of the users. For the purpose of this research, correlation coefficient values greater than 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 are illustrated in different plots. Each plot represents the magnitude of the interrelationships among the two performance metrics above the particular threshold. For instance, Figure 4.4 shows all the absolute values of the correlation coefficient.

However, Figure 4.11 to Figure 4.13 are used for more precise analysis of these interrelationships as they illustrates correlation coefficient absolute value greater than 0.7, 0.8 and 0.9, which are recognised as significant correlation coefficient values. These interrelationships are illustrated by green and yellow colours. For instance, Overall Equipment Efficiency and customer satisfaction have very high interrelationships with absolute correlation coefficient values greater than 0.9.

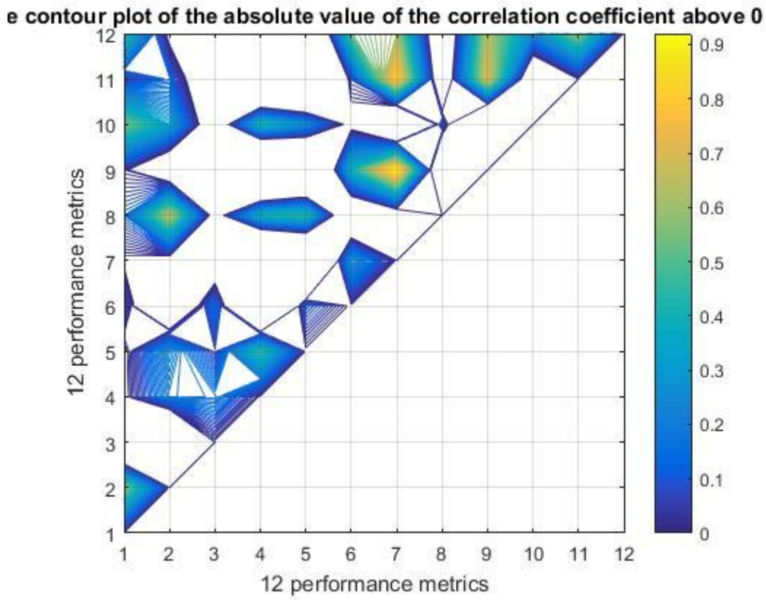

Figure 4.4: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0

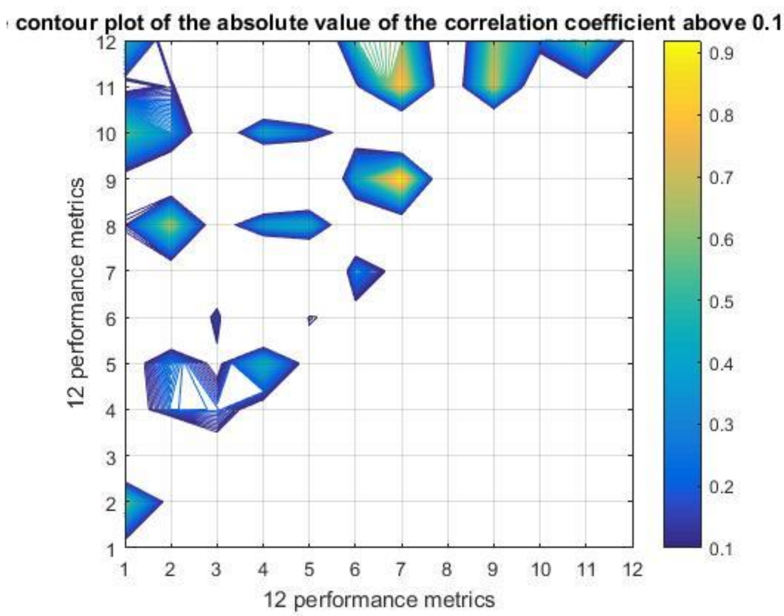

Figure 4.5: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.1.

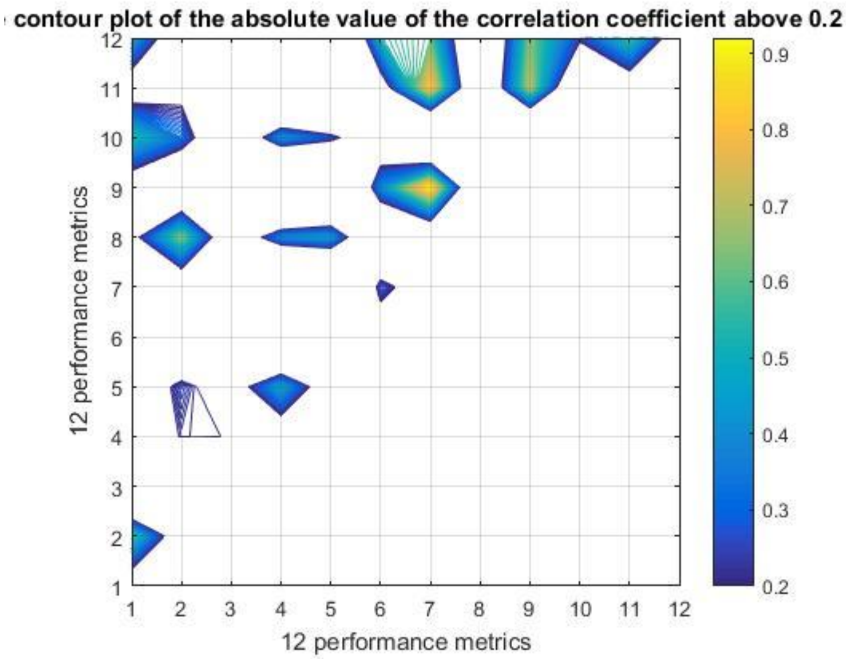

Figure 4.6: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.2.

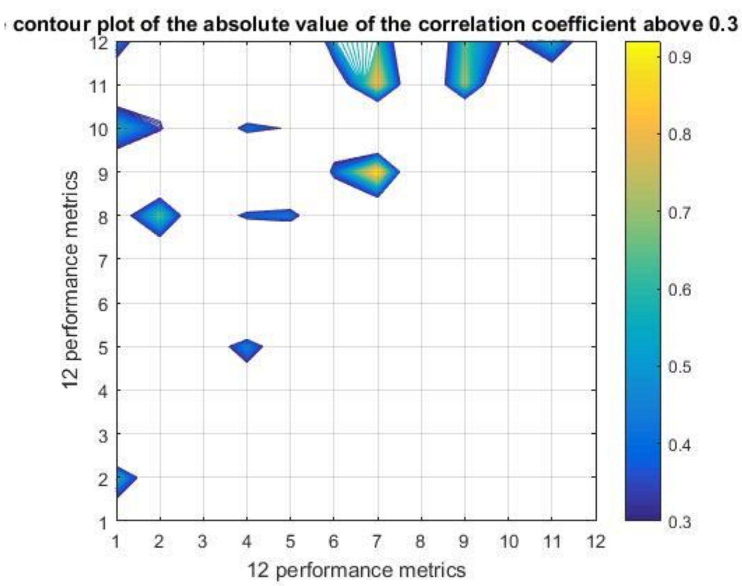

Figure 4.7: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.3.

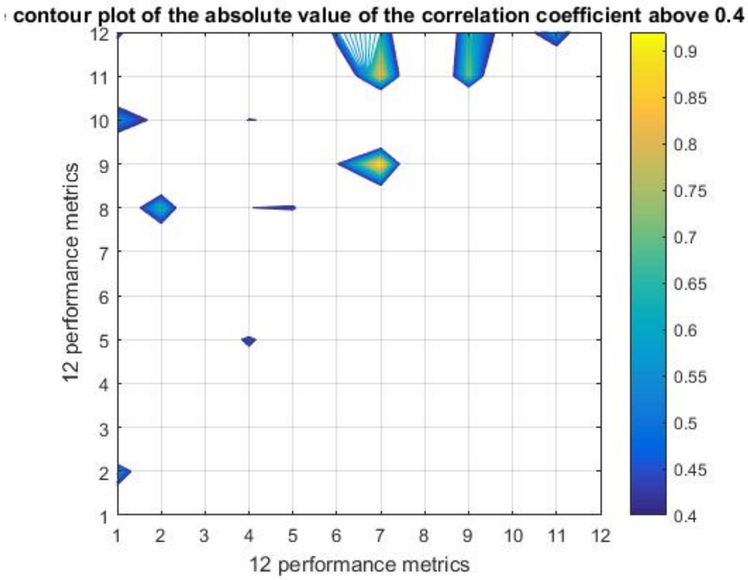

Figure 4.8: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.4.

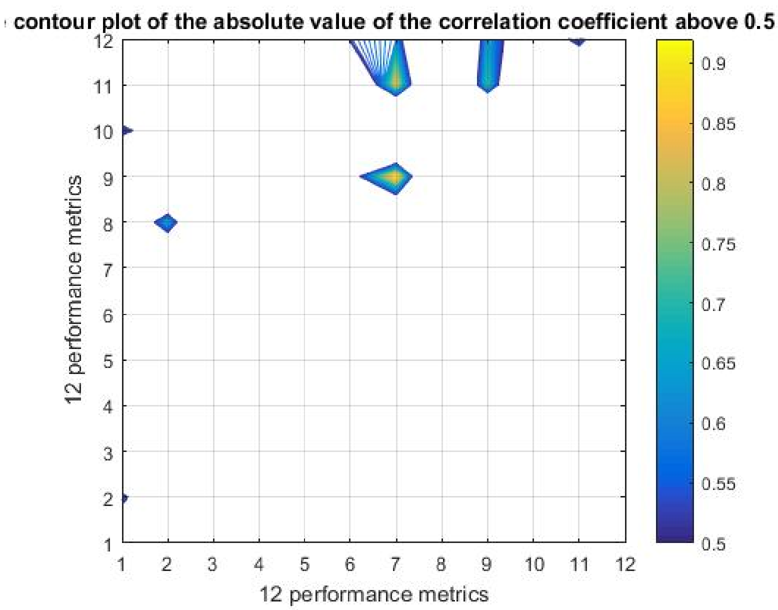

Figure 4.9: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.5.

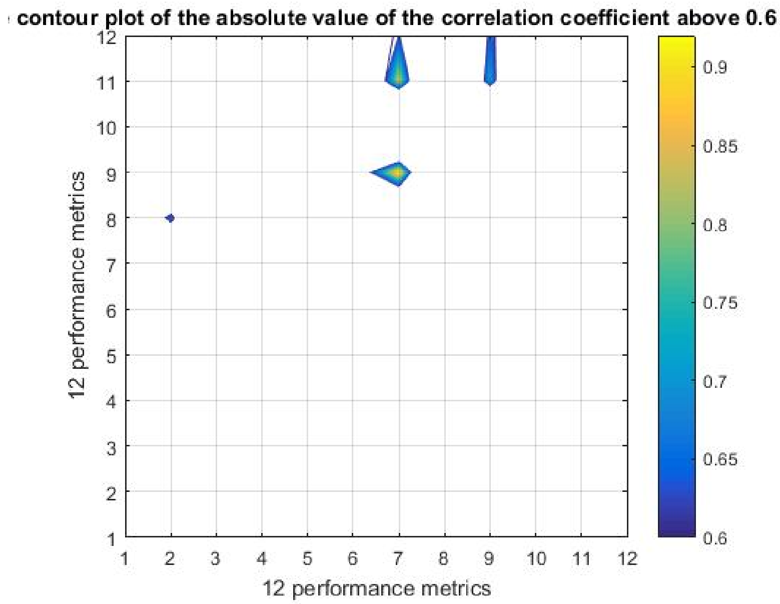

Figure 4.10: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.6.

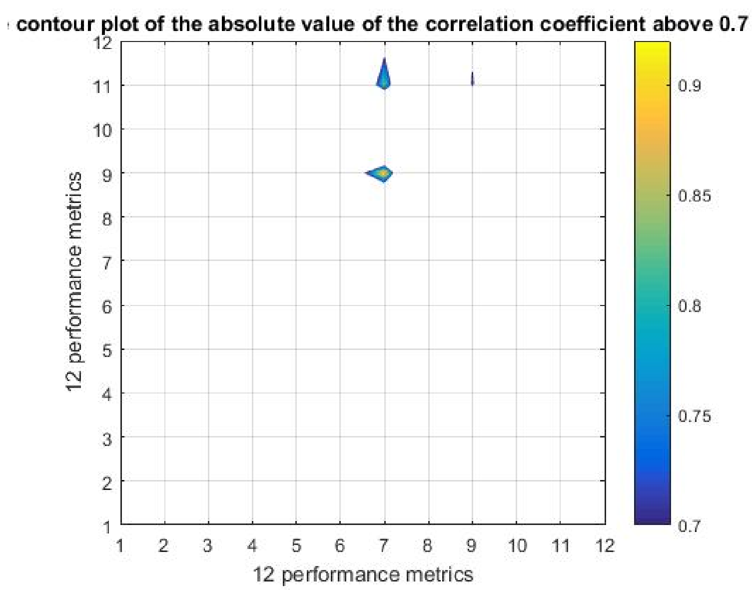

Figure 4.11: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.7.

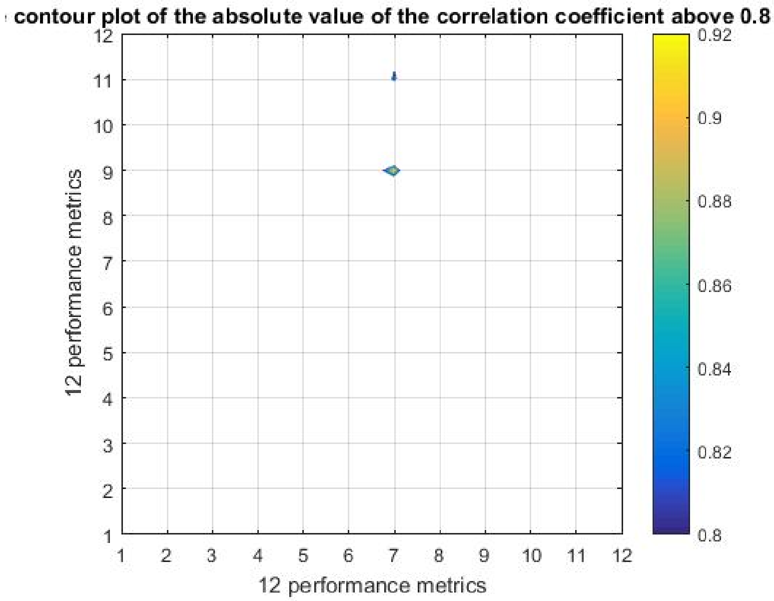

Figure 4.12: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.8.

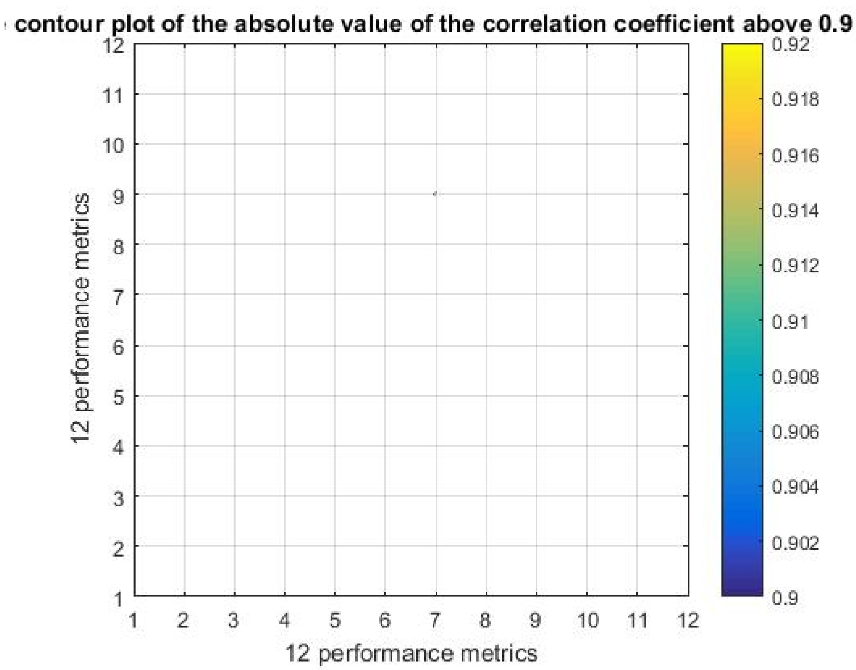

Figure 4.13: The contour plot of the magnitude of the correlation coefficient of 12 performance metrics above 0.9.

Also, setup time has a high relationship with overall equipment efficiency (OEE), and customer satisfaction with absolute correlation coefficient as they have values greater than 0.8. Therefore, in order to demonstrate the correlation coefficient values, different thresholds can be specified.

Moreover, the MATLAB code can presents the list of pair of performance metrics for each threshold. The results associated with the correlation coefficient values greater than 0.7 are presented in Table 4.2.

From this table, it can be inferred that the setup time has a strong interrelationship with OEE, customer satisfaction and supplier responsiveness. Also, OEE is interrelated with customer satisfaction and supplier responsiveness, and manufacturing lead time and customer satisfaction are related to supplier responsiveness.

Table 4.2: The pair performance metrics with 0.7, 0.8 and 0.9 correlation coefficient value

Threshold	**Interrelated performance metrics**	
0.9	Overall Equipment Efficiency	Customer satisfaction
0.8	Setup time	Overall Equipment Efficiency
		Customer satisfaction
	Overall Equipment Efficiency	Supplier responsiveness
		Customer satisfaction
0.7	Setup time	Overall Equipment Efficiency
		Customer satisfaction
		Supplier responsiveness
	Overall Equipment Efficiency	Customer satisfaction
		Supplier responsiveness
	Manufacturing lead time	Supplier responsiveness
	Customer satisfaction	Supplier responsiveness

However, these plots can determine that the selected performance indicators have interrelationships and can influence each other during lean implementation. Therefore, it is vital to establish the weighting approach to prioritise them as well as consider their interdependencies in the lean measurement model. In the next section, the fuzzy-based Analytic Network Process (ANP) approach is explained to allocate the relative importance weightings to each identified performance metric.

4.5 Fuzzy-based Analytic Network Process (ANP) approach

In this section, the method for establishing the interrelationships between lean performance measures and performance metrics that are used to assign relative weightings to each performance metric in a fuzzy-based leanness assessment model are explained. Previously, several methods have been used to determine the weightings of performance indicators. However, most of them were not successful in capturing human perceptions effectively. In this respect, Saaty and Takizawa (1986) introduced the Analytic Hierarchy Process (AHP) approach and the more general form of that, the Analytic Network Process (ANP), to generate the relative importance weightings among decision elements. Both methods use matrix manipulation approaches. The AHP helps decision makers to break down a complex problem into a form of simple hierarchy and then establish relative weightings between decision levels using a sequential process of pair-wise comparison. In this approach, each element is supposed to be independent and pair-wise comparison is used to derive the relative importance ratio of the elements in the level of hierarchy associated with an element of the preceding level.

The ANP approach is the generalisation of the AHP approach that allows more complex interrelationships between different criteria to be analysed. In the AHP approach, a unidirectional hierarchical relationship among the decision attributes is utilised, while the ANP approach uses a dynamic multi-directional relationship between these elements. In the ANP, a feedback relationship between different levels is allowed to reconcile the requirements and desires of all stakeholders. Therefore, the ANP is an effective method in situations where the interactions among the elements of the system have a network structure. Contrary to the AHP that uses a strict hierarchical structure, the ANP uses ratio scale measurements based on pairwise comparisons. Therefore, in the ANP, a level can directly or indirectly dominate and be dominated by other decision criteria and levels.

In addition, the ANP approach uses a systems-with-feedback to create the decision problem and to show how to investigate inner and outer dependence with feedback. Inner dependence is interdependence between components combined with feedback among components, while outer dependence is relationship among components associated with feedback circuits.

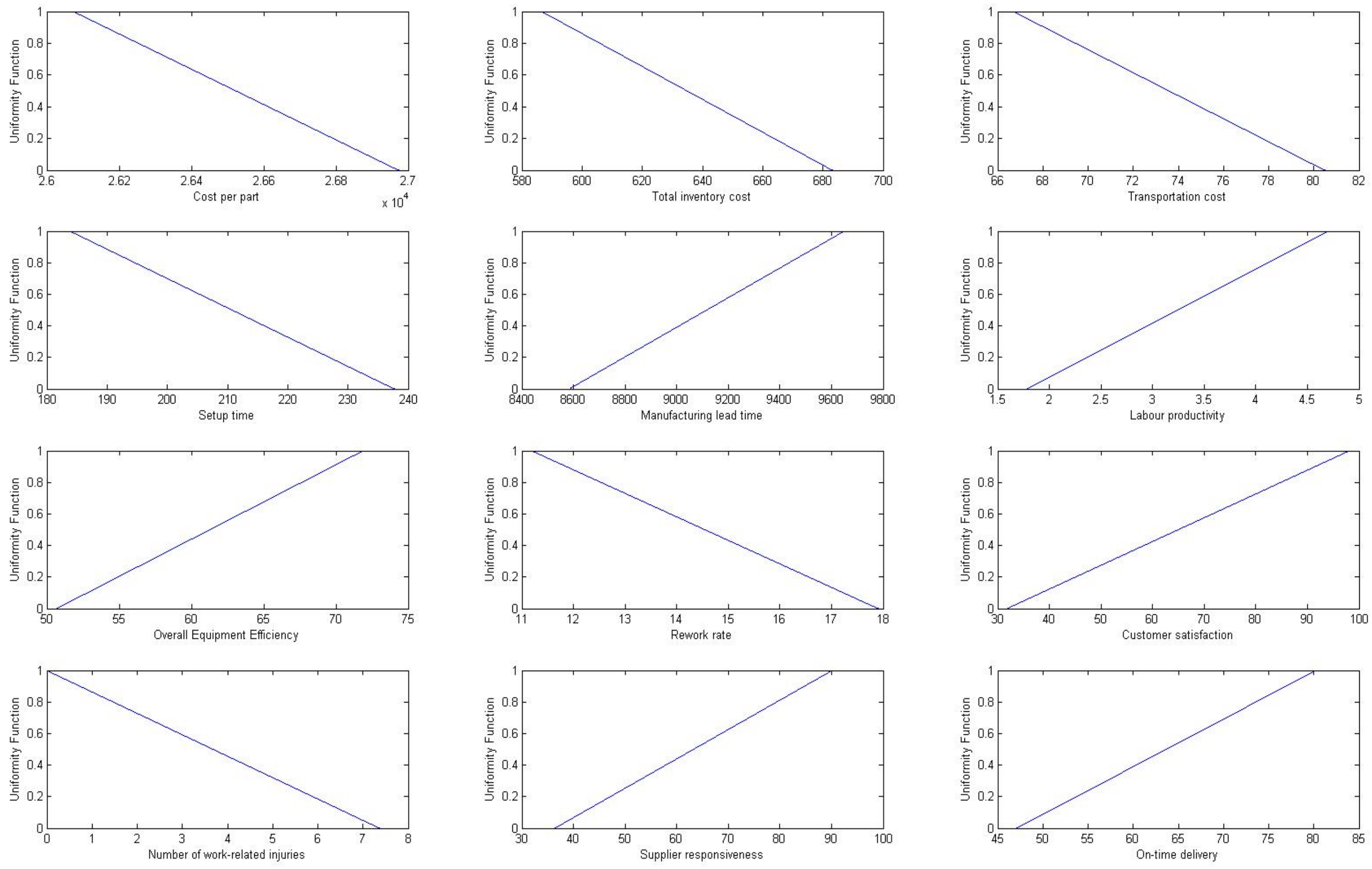

Figure 4.14: Positive and negative variables uniformity conversion.

However, in this approach decision makers express their preferences regarding each attribute in different ways because human judgement varies from person to person. There is always a certain degree of uncertainty and ambiguity in human perception and their judgement described by imprecise language such as equally, moderately, extremely, etc. Therefore, fuzzy set theory is used to deal with this vagueness and imprecision by tackling ambiguities in the process of linguistic assessment of information. Fuzzy set theory proposes a different method to quantify the qualitative judgments. In this research study, triangular numbers are used to evaluate the decision makers' preferences. In fuzzy-based ANP, the linguistic terms are converted into triangular fuzzy numbers to establish pair-wise comparison matrices (Chang 1996; Chan et al. 2003). In this regard, the ANP approach consists of two main steps:

Step 1: construction of the relationship network among lean performance metrics.

Step 2: calculation of the relative importance weightings of each metric and determination of the priorities of the lean performance metrics.

4.5.1 Construction of the relationship network

In this step, the structure of the problem is constructed by establishing the interaction network between all performance measures and metrics. For instance, when performance metric 1 (M_1) depends on performance metric 2 (M_2), the relationship between these two elements is represented by an arrow from M_2 to M_1. Pairwise comparisons and a super matrix are used to evaluate all these relationships. The super matrix is developed to calculate the overall priorities, vectors and cumulative influence of each performance metric on every other metric with which it interacts (Saaty & Takizawa 1986).

The weightings of lean performance measures (PM) are represented by the vector w_1, and w_2 is a matrix that represents the relationship between performance metrics with respect to each lean performance measure. w_3 is a matrix that denotes the interdependent relationships between lean performance measures with respect to each measure. Similarly, w_4 denotes the interdependencies of lean performance metrics with respect to each metric.

The primary inputs required to calculate w_1, w_2, w_3 and w_4 in the ANP technique are pairwise comparison matrices of each elements within each cluster. These matrices are similar to those used in the AHP method (Saaty 1980). In the conventional AHP approach, a discrete scale is used for pairwise comparison. However, human judgements and assessments are usually subjective and imprecise. Therefore, in this research study, all the elements of pairwise comparison matrices are triangular fuzzy numbers (l_i, m_i, u_i). In all pairwise comparison matrices the element a_{ij} represents the comparison of row component *i* with column component *j*. Also, the reciprocal value $1/a_{ij}$ is allocated to the a_{ji} element and (1, 1, 1) is assigned to the element a_{ii}. Figure 4.15 presents the evaluation algorithm used to apply the fuzzy ANP approach to prioritise the identified performance metrics. Based on these pairwise comparisons, the following super matrix is obtained:

$$W = \begin{array}{r} \\ Integrated\ lean\ index\ (LI) \\ Performance\ measures\ (PM) \\ Performance\ metrics\ (PMs) \end{array} \begin{array}{c} \begin{array}{ccc} LI & PM & PMs \end{array} \\ \begin{pmatrix} 0 & 0 & 0 \\ w_1 & w_3 & 0 \\ 0 & w_2 & w_4 \end{pmatrix} \end{array} \qquad \text{Equation 4.24}$$

4.5.2 Fuzzy ANP calculation to assign relative importance weightings

As mentioned earlier, linguistic data are used to calculate pairwise comparison matrices, w_1, w_2, w_3 and w_4. Previously, several methods were developed to determine the interrelationships using fuzzy ANP and fuzzy AHP (Van Laarhoven & Pedrycz 1983; Buckley 1985b; Cheng 1997; Leung & Cao 2000). For this section, to complete the calculation of pairwise comparison and relative importance weightings, the method developed by Cheng (1997) is used in this research study because it is easier to implement compared to other fuzzy AHP methods and conventional AHP methods.

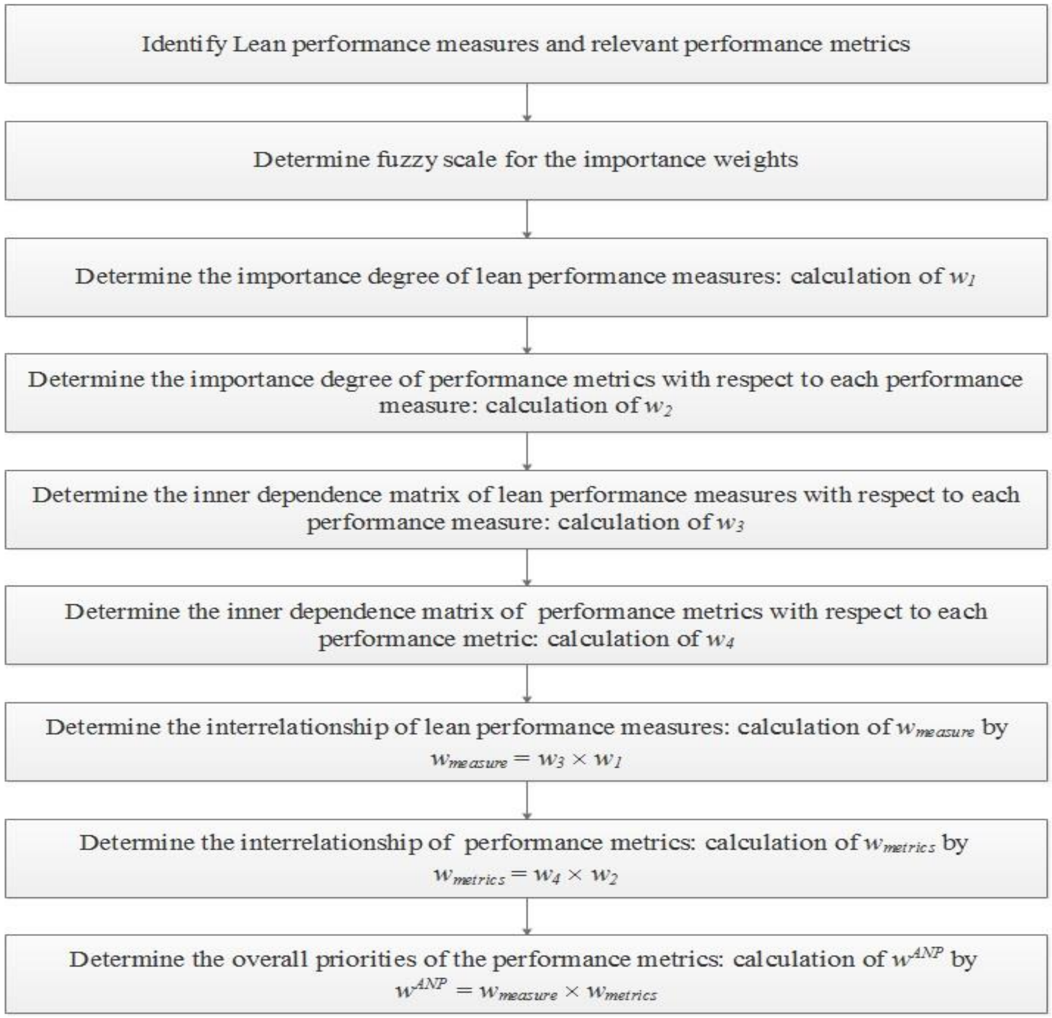

Figure 4.15: The evaluation algorithm steps for determining the overall priorities of performance metrics.

Assume $x = (x_1, x_2, \ldots, x_n)$ is a set of objects and $g = (g_1, g_2, \ldots, g_m)$ is a set of goals. According to the method developed by Chang 1996, an extent analysis for each object with respect to each goal g_i is performed. If $M_{g_i}^{j}$; $j = 1, 2, \ldots, m$; $i = 1, 2, \ldots, n$ are the triangular fuzzy numbers, m extent analysis values are obtained for each of the n objects.

In the next step, the value of fuzzy synthetic extent (S_i) with respect to the i^{th} object is calculated using the following equation:

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} \quad \text{Equation 4.25}$$

To obtain the $\sum_{j=1}^{m} M_{g_i}^{j}$ from this equation, the additional operation of fuzzy numbers from m extent analysis values for a particular matrix is performed:

$$\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{j=1}^{m} l_j \, , \sum_{j=1}^{m} m_j \, , \sum_{j=1}^{m} u_j\right) \quad \text{Equation 4.26}$$

And to obtain $\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1}$ the fuzzy addition operation of $M_{g_i}^{j},\ j = 1, 2, \ldots, m$ is performed (Chang 1996; Lee et al. 2009; Shaw et al. 2012):

$$\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j} = \left(\sum_{i=1}^{n} l_i \, , \sum_{i=1}^{n} m_i \, , \sum_{i=1}^{n} u_i\right) \quad \text{Equation 4.27}$$

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{g_i}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right) \quad \text{Equation 4.28}$$

In the next step, the degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as:

$$V(M_2 \geq M_1) = \sup_{y \geq x}\left[\min(\mu_{M_1}(x), \mu_{M_2}(y)\right] \quad \text{Equation 4.29}$$

Equation 4.29 can be represented as follows:

$$V(M_2 \geq M_1) = \mathrm{hgt}\,(M_1 \cap M_2) = \mu_{M_2}(d)$$
$$= \begin{cases} 1, & if\ m_2 \geq m_1 \\ 0, & if\ l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise \end{cases} \quad \text{Equation 4.30}$$

where d is defined as the highest intersection point D between μ_{M_1} and μ_{M_2}, which is shown in Figure 4.16.

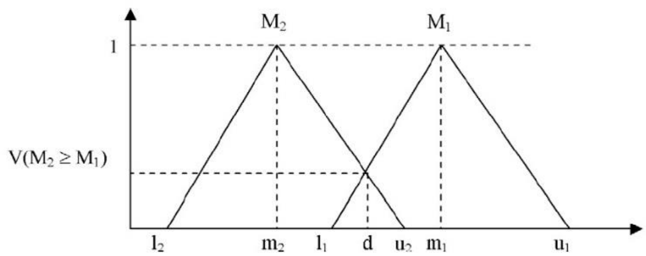

Figure 4.16: The intersection between M_1 and M_2.

A convex fuzzy number can be defined as:

$$V(M \geq M_1, M_2, \ldots, M_k)$$
$$= V[(M \geq M_1), and\ (M \geq M_2) and \ldots and\ (M \geq M_k)]$$
$$=\min \mathrm{V}(\forall_{i=1,2,\ldots,k} \geq M_i)$$ Equation 4.31

Assume that:

$$d'(A_i) = \min V\ (S_i \geq S_k)$$ Equation 4.32

for k=1, 2, …, n ; k≠i. then, based on the above equation, the weight vector of the factors is calculated by:

$$W' = \left(d'(A_1), d'(A_2), \ldots, d'(A_i)\right)^T,$$
$$i = 1, 2, \ldots, n$$ Equation 4.33

Finally, after normalisation, the priority weights are as follows:

$$W = (d(A_1), d(A_2), \ldots, d(A_n))^T$$ Equation 4.34

where W is not a fuzzy number.

4.6 Calculating the overall leanness of the manufacturing process

The fuzzy triangular values using uniformity conversion rules and fuzzy weights are calculated for each performance metric using the fuzzy ANP approach. The overall leanness score is determined using the centroid defuzzification equation (Wang & Mendel 1992; Behrouzi & Wong 2011):

$$Overall\ leanness = \sum_{k=1}^{n} \mu_{ijk} \times w_{ijk} \qquad \text{Equation 4.35}$$

In this equation, μ_{ijk} is performance metric membership value and w_{ijk} is the relative importance weighting for each performance metric. The relative importance weightings add up to 1, so the overall leanness index is calculated by the sum of the values that provide a weighted average leanness value index.

4.7 Validation of the proposed weighted fuzzy-based leanness measurement model using a real-life case study

This section will validate the proposed methodology for measuring the overall leanness index of the production process developed in this research by using a case study approach. In the previous chapter, the background and overview of the selected case study company (one of Australia's leading modular manufacturer, referred to as HMC company in this study) were outlined. Also, several lean strategies were suggested for implementation to improve the identified lean performance metrics and address manufacturing wastes in this company. In this chapter, the developed weighted leanness measurement methodology using fuzzy set theory is explained to measure the impacts of these strategies.

In this research study, Station 4 of the QMC modular construction manufacturing line was selected as the case study manufacturing process, as discussed in Chapter 3. The process in Station 4 consists of the supplier (Station 3), the customer (Station 5) and the manufacturing process. The average manufacturing period to produce one unit of final product is 480 minutes and with $26,500 average total cost per unit of module. The number of orders is 20 modules of two-storey student accommodation that started its production process in the QMC modular construction line. In this batch model of project delivery suited for the construction industry, it is determined to be 20 modules for one specific project. The project should be completed in six months. Therefore, an average of 3.33 modules should be completed each month. As it is mentioned in the case study background, the project was a production and prefabrication of two-storey student accommodation that has 20 modules (of studio apartments). However, despite the considerable competitive advantages of modularisation, the products of the HMC Company are usually 10-20% more expensive than their counterparts, which are built on-site. Therefore, the HMC Company was limited to customers such as the government, wireless providers and education sectors that are less concerned about cost. Like other modular manufacturers, the reason for the high cost of their products is mainly due to their failure to take advantage of modern manufacturing technologies to improve their production process. Hence, it is very difficult for the organisation to compete in their market, sustain production and meet customer requirements. For these reasons, the company was keen to adopt lean manufacturing principles and implement one of the suggested lean initiatives to take the first step in improving the manufacturing performance of the company.

The identified lean performance metrics were cost per part[6], total inventory cost, transportation cost, setup time, manufacturing lead time, labour productivity, overall equipment efficiency, rework rate, customer satisfaction, number of work-related injuries, supplier responsiveness and on-time delivery. The targeted wastes were excess movements, setup time, defects, excess transportation, final goods inventory, over processing, failure time, work-in-process, raw materials inventory, and knowledge disconnection. It was mentioned in the previous chapter that the most appropriate lean strategies based on the relationships between the selected lean tools, performance metrics and manufacturing wastes are JIT, Cellular Manufacturing, the Kanban system, Standard Work Process, SMED, 5S, TPM and Production Smoothing. To evaluate the improvement achieved by implementing the selected lean techniques, it is important to evaluate and assess the leanness status of the existing performance in comparison with the improved process. Therefore, the weighted leanness evaluation model that measures the integrated leanness score by considering

[6] It is the cost of producing one module.

the interrelationships between lean performance metrics was developed and discussed in this chapter.

This section explained the application of the proposed model in the QMC modular construction line to evaluate the production process at Station 4. During the course of this research one lean strategy was implemented in the manufacturing line and the leanness score of Station 4 was measured before and after lean implementation. Therefore, before applying any lean techniques in the production process, the current leanness value using the weighted leanness measurement methodology was used.

4.7.1 Identifying the scope of the study

Accurate identification of the study scope helps the lean team to implement the leanness assessment model efficiently. In the manufacturing process, the scope of study can be a workstation, a specific manufacturing line, a sector in the organisation or the entire organisation. In this research study, Station 4 was selected as the scope as it is the best target for implementation of a lean strategy.

Process mapping assists the lean team to understand all activities and operations in the manufacturing line. Value stream mapping (VSM) is used to identify customers, suppliers, operations, buffering area and offline inventories in the selected study scope. This step helps to identify the necessary and unnecessary activities in the manufacturing line.

To obtain the raw data for this station, unstructured interviews, the researcher’s observation and archival data were used. The manufacturing process and operations at Station 4 were analysed during regular visits by the researcher. The detailed description of this workstation was provided in Chapter 3.

4.7.2 Identifying lean performance metrics

After defining the study scope, the relevant performance metrics should be selected for the identified scope. These performance measures should reflect the organisation’s goals of evaluate the production performance effectively. Selecting a set of performance metrics can add more value to the organisation and the customer. However, for effective evaluation of the performance, the number of established performance metrics should be minimised as much as possible and adoption of these metrics should be related to the organisation's characteristics and specifications. In this step, a set of appropriate lean performance metrics, from both cost and benefit metrics, is identified for the scope of the study. The cost metrics are negatively correlated with the overall performance of the organisation, while benefit metrics indicate the positive impacts on the overall leanness.

In the previous chapter, different performance indicators were identified for Station 4 of the QMC modular manufacturing line. These metrics are from the financial, productivity, quality, safety and flexibility measures. After several discussions with the top managers, twelve performance metrics were selected for this workstation. These metrics are divided into quantitative and qualitative metrics. Quantitative metrics are measured using numerical terms and qualitative metrics are measured using linguistic terms. As these performance metrics are defined for Station 4, the suppliers are Station 3 and the warehouse, the customer is Station 5 and the manufacturing system is Station 4. These performance metrics and their measurement units are provided in Table 4.3.

Table 4.3: The selected performance indicators for the study's scope and their relevant lean goals

Performance measure	Performance metric	Qualitative	Quantitative	Metric type	Lean goal
Financial	Cost per part (dollars per unit)		√	Cost	↓
	Total inventory cost (dollars per unit per day)		√	Cost	↓
	Transportation cost (dollars per unit per day)		√	Cost	↓
Productivity	Setup time (minutes)		√	Cost	↓
	Manufacturing lead time (hours)		√	Cost	↓
	Labour productivity (unit per day)		√	Benefit	↑
	Overall Equipment Efficiency (%)		√	Benefit	↑
Quality	Rework rate (%)		√	Cost	↓
	Customer satisfaction (%)	√		Benefit	↑
Safety	Number of work-related injuries (accidents per day)		√	Cost	↓
Flexibility	Supplier responsiveness (%)	√		Benefit	↑
	On-time delivery (%)	√		Benefit	↑

4.7.3 Data collection for the weighted leanness measurement methodology

As mentioned in the previous section, numerical and linguistic terms are used to measure the quantitative and qualitative metrics respectively. In this section, the numerical and linguistic data for the selected performance metrics are collected. The relevant data for two types of performance metrics were collected from the financial and commercial, production and engineering, quality control, supply chain and marketing departments. To measure the quantitative metrics, the historical data of the organisation; such as production duration, required resources, production expenses and supplier responsiveness, were used. These variables represent the resources and efforts used to carry out the manufacturing process. Table 4.4 presents eight fuzzy linguistic terms used to evaluate the qualitative variables (Herrera et al. 2000). Table 4.5 provides the collected data for the selected performance metrics. The performance metrics were measured based on the definition provided in Appendix B. To determine the fuzzy triangular numbers for each metric, ten observations have been taken for Station 4 at different situations or the same situation at different times. In the next section, the raw values of the metrics are transformed into triangular fuzzy numbers (TFN) using Equation 4.5 to Equation 4.12.

Table 4.4: Qualitative linguistic terms and their corresponding values

Linguistic term	Range (%)
None (N)	0
Very low (VL)	0 < R < 20
Low (L)	20 < R < 40
Medium (M)	40 < R < 60
Medium high (MH)	60 < R < 70
High (H)	70 < R < 80
Very high (VH)	80 < R < 90
Perfect (P)	R > 90

4.7.4 Converting raw data from the manufacturing performance into TFN

This section follows the instructions provided in Section 4.4.1 to calculate fuzzy triangular numbers from the quantitative and qualitative data.. Then, the differences between adjacent data were calculated using Equation 4.5. The difference values are used to calculate the similarity from difference values. To calculate the similarity value, the standard deviation values are calculated using Equation 4.7 and the similarity values were quantified by Equation 4.6. Then, the centre vertex point ‘b’ was calculated using Equation 4.8. In addition, the vertex point ‘a’ and extreme point ‘c’ can be found using Equation 4.9 and Equation 4.10. Table 4.5 presents triangular fuzzy numbers for each performance metric and Figure 4.17 shows the graphical representation of the membership function for each performance metric.

Table 4.5: Collected values for the performance metrics

Performance measure	Performance metric	Observations									
		1	2	3	4	5	6	7	8	9	10
Financial	Cost per part (dollars per unit)	26153	26640	26230	26145	26835	26645	26430	27230	26310	26980
	Total inventory cost (dollars per unit per day)	625	710	592.5	612.5	633.5	680	611.5	647	608	672.5
	Transportation cost (dollars per unit per day)	78.5	72.5	79.5	74.5	79.5	67.8	68.25	69.8	78.75	68.75
Productivity	Setup time (minutes)	220	278.5	210.5	195.1	189.7	185.7	265.9	235	225.4	190.85
	Manufacturing lead time (hours)	9125	9685	9250	8975	8665	9255	8755	9535	9785	8975
	Labour productivity (unit per day)	2.1	3.1	1.9	4.5	3.2	2.5	2.6	5.9	5.7	3.9
	Overall Equipment efficiency (%)	76.8	50.7	52.9	64.8	71.9	57.2	54.9	66.8	61.9	75.4
Quality	Rework rate (%)	14.3	14.8	12.65	11.5	13.7	17.5	18.4	15.3	17.6	14.7
	Customer satisfaction (%)	40	50	60	90	85	75	85	45	60	65
Safety	Number of work-related injuries (accidents per day)	6	5	1	3	3	1	2	8	5	9
Flexibility	Supplier responsiveness (%)	45	55	68	78	85	90	65	50	40	85
	On-time delivery (%)	50	55	64	85	76	55	70	60	65	80

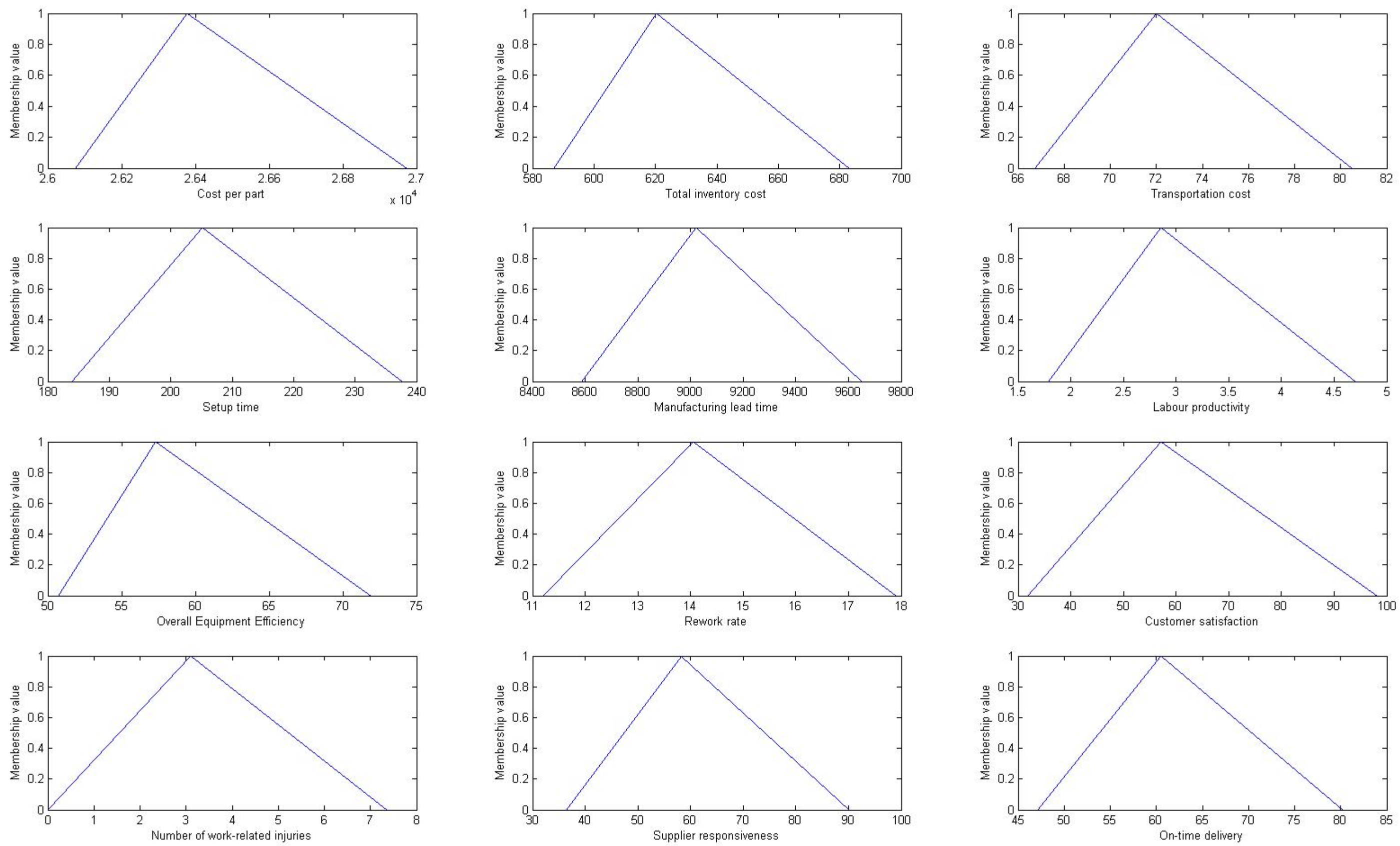

Figure 4.17: Membership function of selected performance metrics.

4.7.5 Determine lean ranges for each performance metric

Identifying the lean range for each performance metric depends on its negative or positive behaviour. Therefore, according to Equation 4.13 to Equation 4.18, the target for all performance metrics is to achieve point 'b' (where the membership value is the maximum). Based on Table 4.6, the triangular fuzzy numbers for setup time at Station 4 of the QMC modular manufacturing line are (183.90, 205.21, 237.75). This performance metric has a negative impact on the overall leanness of the manufacturing. Therefore, the manufacturer aims to reduce the setup time at this station to the minimum point (point 'a'). However, the leanness value of setup time at this point is 0. Therefore, as mentioned in the previous section, the target is to reduce the setup time to 'b'. Hence, the optimum point for setup time at Station 4 is 205.21 minutes. This means that the focus of the manufacturer should be on implementing a lean strategy that reduces setup time from 237.75 minutes to 205.21 minutes.

Therefore, after determining the triangular fuzzy number for each metric, the optimum range and the optimum point for all performance metrics are identified using Equation 4.15 to Equation 4.18. Also, these calculations are based on the behaviour of the performance metric. As mentioned earlier, the company will revise and recalculate the target for implementing more lean strategies after achieving the optimum value. These lean ranges can be used as a sense of direction for improvement during lean implementation as well as implementation of limits for Station 4. Table 4.6 provides the lean ranges for different performance metrics.

4.7.6 Assigning fuzzy relative importance weightings using the fuzzy ANP approach

In this section, the proposed method for determining the relative importance weightings of performance metrics is presented. The fuzzy Analytic Network Process (ANP) is explained in section 4.5. Due to limited space, only a limited number of pairwise comparisons are presented in this section and all calculations are provided in Appendix I.

Table 4.6: Performance metrics lean range for implementing lean strategies

Performance metrics	a	b	c	Improvement direction	Lean range	Behaviour
Cost per part (dollars per unit)	26074.46	26377.37	26973.92	c to b	26377.37-26973.92	Negative
Total inventory cost (dollars per unit per day)	586.74	620.43	683.24	c to b	620.43-683.24	Negative
Transportation cost (dollars per unit per day)	66.71	72.02	80.49	c to b	72.02-80.49	Negative
Setup time (minutes)	183.90	205.21	237.75	c to b	205.21-237.75	Negative
Manufacturing lead time (hours)	8584.76	9021.71	9650.46	c to b	9021.71-9650.46	Negative
Labour productivity (unit per day)	1.78	2.85	4.70	a to b	1.78-2.85	Positive
Overall equipment efficiency (%)	50.70	57.31	71.90	a to b	50.70-57.31	Positive
Rework rate (%)	11.20	14.05	17.91	c to b	14.05-17.91	Negative
Customer satisfaction (%)	31.88	57.13	98.21	a to b	31.88-57.13	Positive
Number of work-related injuries (accident per day)	0	3.10	7.37	c to b	3.10-7.37	Negative
Supplier responsiveness (%)	36.46	58.24	90.20	a to b	36.46-58.24	Positive
On-time delivery (%)	47.13	60.46	80.26	a to b	47.13-60.46	Positive

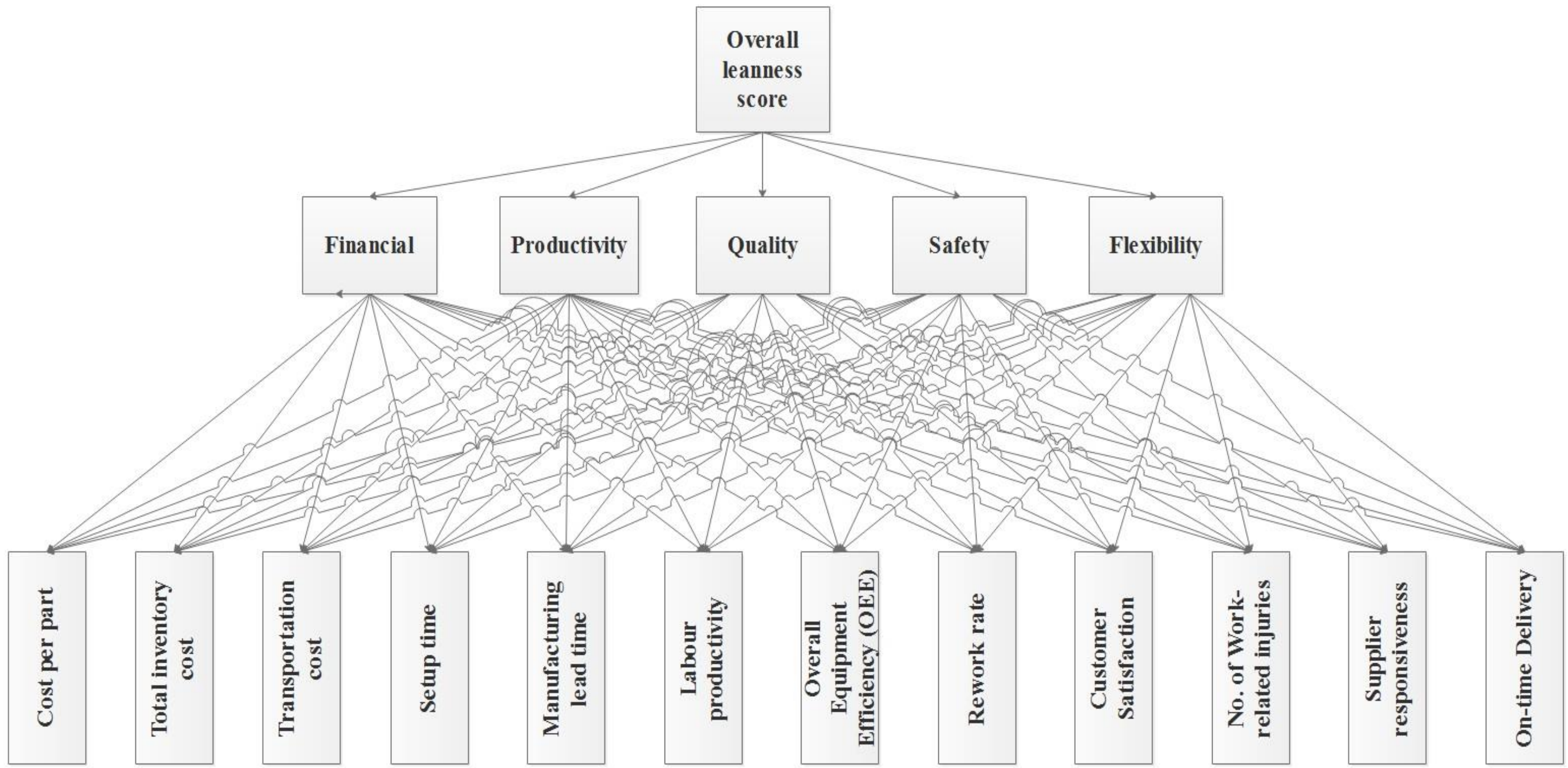

Figure 4.18: ANP-based framework for lean performance measures and performance metrics.

Step 1. The ANP network system is created by relating lean performance measures and lean performance metrics. Figure 4.18 illustrates the ANP interrelationship network between lean performance measures and metrics.

Step 2. The triangular fuzzy conversion scale is developed. The ranges of fuzzy triangular scales are from equally important/preferred (1, 1, 1) to extremely important/preferred (8, 9, 9). The remaining fuzzy values are presented in Table 4.7.

Table 4.7: Fuzzy pairwise comparison scale

Description	**Fuzzy scale**	**Reciprocal**
Equally important/ preferred	(1, 1, 1)	(1, 1, 1)
Equally to moderately important/ preferred	(1 , 2, 3)	(1/3, 1/2, 1)
Moderately important/ preferred	(2, 3, 4)	(1/4, 1/3, 1/2)
Moderately to strongly important/ preferred	(3, 4, 5)	(1/5, 1/4, 1/3)
Strongly important/ preferred	(4, 5, 6)	(1/6, 1/5, 1/4)
Strongly to very strongly important/ preferred	(5, 6, 7)	(1/7, 1/6, 1/5)
Very strongly important/ preferred	(6, 7, 8)	(1/8, 1/7, 1/6)
Very strongly to extremely important/ preferred	(7, 8, 9)	(1/9, 1/8, 1/7)
extremely important/ preferred	(8, 9, 9)	(1/9, 1/9, 1/8)

Step 3. If it is assumed that there is no dependence among lean performance measures, then the pairwise comparison among lean performance measures with respect to lean goals is established using the linguistic variables in Table 4.7. The comparison results are in Table 4.8.

Table 4.8: Pairwise comparison of lean performance metrics assuming no dependence among them

Overall leanness index	Financial	Productivity	Quality	Safety	Flexibility
Financial	(1, 1, 1)	(1 , 2, 3)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
Productivity		(1, 1, 1)	(1 , 2, 3)	(2, 3, 4)	(1 , 2, 3)
Quality			(1, 1, 1)	(2, 3, 4)	(1 , 2, 3)
Safety				(1, 1, 1)	(1 , 2, 3)
Flexibility					(1, 1, 1)

Based on the pairwise comparison and the fuzzy conversions scale in Table 4.7, the following eigenvector for the lean performance measures is obtained by performing the extent analysis of the fuzzy AHP methodology with respect to the lean goal:

$$w_1 = \begin{pmatrix} Financial \\ Productivity \\ Quality \\ Safety \\ Flexibility \end{pmatrix} = \begin{pmatrix} 0.4181 \\ 0.2975 \\ 0.2285 \\ 0.0526 \\ 0.0033 \end{pmatrix}$$

Step 4. In this stage, it is assumed that there is no dependence among performance metrics; thus, metrics are compared with respect to each performance measure to yield each column of Table 4.10. For instance, one possible question to obtain the relative importance of performance metrics with respect to the financial measure is, “what is the relative importance of total inventory cost when compared to rework rate with respect to financial measures?” This yields strongly important as represented in Table 4.9. The degree of relative importance weightings of the metrics for the remaining lean performance measures is calculated in a similar way and presented in Table 4.10.

Table 4.9: Relative importance of performance metrics associated with financial measures

Financial	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1,2,3)	(5,6,7,)	(3,4,5)	(7,8,9)	(3,4,5)	(2,3,4)	(6,7,8)	(5,6,7)	(4,5,6)	(5,6,7)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(3,4,5)	(4,5,6)	(5,6,7)	(3,4,5)	(4,5,6)	(5,6,7)	(6,7,8)	(4,5,6)	(6,7,8)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(2,3,4)	(6,7,8)	(4,5,6)	(2,3,4)	(5,6,7)	(5,6,7)	(6,7,8)	(4,5,6)	0.20
Setup time				(1,1,1)	(1,2,3)	(5,6,7)	(2,3,4)	(3,4,5)	(6,7,8)	(7,8,9)	(4,5,6)	(2,3,4)	0.14
Manufacturing lead time					(1,1,1)	(5,6,7)	(2,3,4)	(2,3,4)	(5,6,7)	(6,7,8)	(4,5,6)	(1,2,3)	0.11
Labour productivity						(1,1,1)	(1/4,1/3,1/2)	(1,2,3)	(4,5,6)	(3,4,5)	(2,3,4)	(1/5,1/4,1/3)	0
Overall equipment efficiency							(1,1,1)	(3,4,5)	(5,6,7)	(6,7,8)	(5,6,7)	(1,2,3)	0.07
Rework rate								(1,1,1)	(3,4,5)	(6,7,8)	(2,3,4)	(1/6,1/5,1/4)	0
Customer satisfaction									(1,1,1)	(3,4,5)	(2,3,4)	(1/5,1/4,1/3)	0
No of work-related injuries										(1,1,1)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	0
Supplier responsiveness											(1,1,1)	(1/3,1/2,1)	0
On-time delivery												(1,1,1)	0.03

Table 4.10: The column eigenvectors of performance metrics with respect to each lean performance measures

W_2	Financial	Productivity	Quality	Safety	Flexibility
Cost per part	0.23	0.07	0.11	0.14	0.08
Total inventory cost	0.22	0	0.09	0.10	0.05
Transportation cost	0.20	0	0.12	0.13	0
Setup time	0.14	0.29	0.13	0.18	0.10
Manufacturing lead time	0.11	0.21	0.08	0	0
Labour productivity	0	0.17	0	0	0
Overall equipment efficiency	0.07	0.23	0.03	0	0
Rework rate	0	0.02	0.21	0	0
Customer satisfaction	0	0	0.19	0	0
No of work-related injuries	0	0	0	0.44	0
Supplier responsiveness	0	0	0	0	0.43
On-time delivery	0.03	0	0.03	0	0.34

Step 5. In this step, the inner dependence among lean performance measures is determined through analysing the impacts of each lean performance measure on other measures using pairwise comparisons. For example, one possible question is, "what is the relative importance of financial measures when compared with quality measures for controlling productivity measures?" The resulting eigenvectors obtained from the pairwise comparison are presented in Table 4.11.

Step 6. In this step, the interrelationships between performance metrics are determined. As previously accomplished for lean performance measures, the inner dependencies are determined and the required pairwise comparison is performed. In this respect, one example for questions used for this step is, "what is the relative importance of total inventory cost when compared with on-time delivery for controlling the cost per part?" The relative importance weightings of the selected performance metrics obtained from the pairwise comparison are presented in Table 4.12.

Table 4.11: The inner dependence matrix of the lean performance measures

W_3	Financial	Productivity	Quality	Safety	Flexibility
Financial	0.84	0.25	0.30	0.34	0.31
Productivity	0.16	0.73	0.09	0.16	0.16
Quality	0	0.01	0.61	0	0.09
Safety	0	0	0	0.50	0
Flexibility	0	0	0.09	0	0.44

Step 7. In this step, the interdependent priorities among lean performance metrics are obtained using:

$$w_{measures} = w_3 \times w_1$$

Step 8. In this step the interdependent priorities of the selected performance metrics are calculated as follows:

$$w_{metrics} = w_4 \times w_2$$

Step 9. Finally, the overall priorities of performance metrics, w^{ANP}, reflecting the interrelationships between the selected performance metrics are calculated as follows:

$$w^{ANP} = w_{measures} \times w_{metrics}$$

$$w^{ANP} = \begin{pmatrix} Cost\ per\ part \\ Total\ inventory\ cost \\ Transportation\ cost \\ Setup\ time \\ Manufacturing\ lead\ time \\ Labour\ productivity \\ Overall\ equipment\ efficiency \\ Rework\ rate \\ Customer\ satisfaction \\ No.of\ work-related\ injuries \\ Supplier\ responsiveness \\ On-time\ delivery \end{pmatrix} = \begin{pmatrix} 0.1989 \\ 0.1888 \\ 0.1853 \\ 0.1544 \\ 0.1105 \\ 0.0487 \\ 0.0567 \\ 0.0262 \\ 0.0085 \\ 0.0026 \\ 0.0018 \\ 0.0193 \end{pmatrix}$$

Table 4.12: The column eigenvectors of performance metrics with respect to each performance metric

W_4	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No of work-related injuries	Supplier responsiveness	On-time delivery
Cost per part	0.2842	0.2117	0.2126	0.1659	0.1487	0.1932	0.1945	0.1628	0.1831	0.1459	0.1727	0.1644
Total inventory cost	0.2492	0.2190	0.2081	0.1890	0.1497	0.1669	0.1370	0.1517	0.1473	0.1476	0.1440	0.1474
Transportation cost	0.2178	0.1779	0.2844	0.2003	0.1638	0.1152	0.1134	0.1354	0.1623	0.1586	0.1690	0.0961
Setup time	0.1296	0.1357	0.1426	0.2205	0.2079	0.0829	0.1418	0.1104	0.0360	0.0817	0.1108	0.1090
Manufacturing lead time	0.0878	0.2140	0.1263	0.1115	0.2079	0.0743	0.0208	0.0694	0.0748	0.0832	0.0905	0.2202
Labour productivity	0.0314	0.0508	0.0000	0.0705	0.0524	0.2310	0.0078	0.0280	0.0000	0.0886	0.0000	0.0613
Overall equipment efficiency	0.0000	0.0479	0.0000	0.0154	0.0277	0.0563	0.3040	0.1188	0.0376	0.0216	0.0000	0.0229
Rework rate	0.0000	0.0347	0.0000	0.0000	0.0000	0.0801	0.0807	0.2181	0.0000	0.0000	0.0000	0.0000
Customer satisfaction	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3073	0.0000	0.0000	0.0000
No of work-related injuries	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2258	0.0000	0.0000
Supplier responsiveness	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2898	0.0000
On-time delivery	0.0000	0.0000	0.0260	0.0268	0.0420	0.0000	0.0000	0.0000	0.0516	0.0470	0.0231	0.1787

The fuzzy ANP analysis results show that the most important performance metric is cost per part (generated with the relative importance value of 0.19), which is more important than all the other performance metrics. Total inventory cost with a relative important weighting of 0.18 is the second-most important performance metric. Supplier responsiveness and number of work-related injuries are the least important performance metrics according to the fuzzy ANP analysis.

4.7.7 Weighted overall leanness index

In this stage, the inputs are fuzzified and the performance variables are obtained. To calculate the fuzzy membership values of metrics, Equation 4.19 and Equation 4.20 are used. The overall leanness value considering the interrelationships between lean performance metrics are calculated using the developed weighted fuzzy-based leanness assessment model and Equation 4.35. In this regard, Table 4.13 presents the leanness values and relative importance weightings of each performance metric as well as the optimum leanness values and the overall leanness index.

It can be seen from Table 4.13 that the overall leanness value of Station 4 in the QMC modular manufacturing line is 24.83 out of 100 without considering the relative importance weightings of performance metrics. In addition, this table shows the individual leanness value of each performance metric. However, as mentioned earlier lean performance metrics can influence each other. Therefore, it is important to consider the interdependent relationships between performance metrics and allocate relative importance values to each metric when assessing the overall leanness of the manufacturing line. In this regard, this research study proposed the weighted leanness assessment model that considers these interdependent relationships to assess the overall leanness index. Hence, the overall leanness value of Station 4 based on the proposed model in this research is 23.87 out of 100. Also, the individual leanness scores of each metric are presented in Table 4.13. Furthermore, where equal interrelationships between lean performance metrics are considered, customer satisfaction and rework rate demonstrate the lowest leanness score among other metrics whereas manufacturing lead time has the highest leanness value. However, different leanness indexes are obtained when considering the interdependent relationships between metrics by multiplying the leanness value of metrics by the relative importance weightings. Thus, supplier responsiveness and customer satisfaction have the lowest leanness values when the interrelationships between lean performance metrics are considered and cost per part is highest in comparison to other metrics.

The optimum leanness score at optimum point 'b' is calculated for selected performance metrics with equal and unequal interrelationships between performance metrics. The overall optimum leanness index considering equal relationships between performance metrics is 0.6158. However, this value changes to 0.6305 when different importance weightings are assigned to each performance metric. After reaching the optimum leanness level, the company will revise the target by repeating the proposed method and implementing other suggested lean techniques to reach the new leanness target. This is because lean manufacturing implementation should be seen as a direction for improvement rather than as a situation to be reached.

Table 4.13: The leanness value of each performance metric considering the relative importance weightings.

Performance metric	Current metric value	Relative importance weighting	Current leanness value considering no weightings	Current leanness value considering relative weightings	Optimum leanness values	Optimum leanness value considering no weightings	Optimum leanness value considering relative weightings
Cost per part (dollar per unit)	26690	0.1989	0.2300	0.0457	26377.37	0.6600	0.131274
Total inventory cost (dollar per unit per day)	655.40	0.1888	0.2000	0.0378	620.43	0.6500	0.12272
Transportation cost (dollar per unit per day)	77.30	0.1853	0.2300	0.0426	72.02	0.6100	0.113033
Setup time (min)	225.30	0.1544	0.2300	0.0355	205.21	0.6000	0.09264
Manufacturing lead time (hours)	9294	0.1105	0.3300	0.0365	9021.71	0.5900	0.065195
Labour productivity (unit per day)	2.65	0.0487	0.3000	0.0146	2.85	0.6300	0.030681
Overall equipment efficiency (%)	55.60	0.0567	0.2300	0.0130	57.31	0.6900	0.039123
Rework rate (%)	16.40	0.0262	0.2200	0.0058	14.05	0.5700	0.014934
Customer satisfaction (%)	45	0.0085	0.2000	0.0017	57.13	0.6200	0.00527
Number of work-related injuries (accident per day)	5	0.0026	0.3200	0.0008	3.10	0.5800	0.001508
Supplier responsiveness (%)	50	0.0002	0.2500	0.0001	58.24	0.5900	0.000118
On-time delivery (%)	55	0.0193	0.2400	0.0046	60.46	0.6000	0.01158
Overall leanness value			**0.2483**	**0.2387**		**0.6158**	**0.6305**

Figure 4.19 shows the current and optimum leanness values of individual performance metrics considering equal relationships between them. Figure 4.20 shows current leanness and optimum leanness values of performance metrics considering interdependent relationships between metrics at Station 4 in the QMC manufacturing line. It can be seen from these two figures that there is a gap between the current leanness level and the optimum leanness for Station 4 at the QMC manufacturing line. Therefore, the targets for the manufacturing company is to achieve the optimum leanness level, measure the new optimum leanness level and define a new target for implementing further appropriate lean strategies.

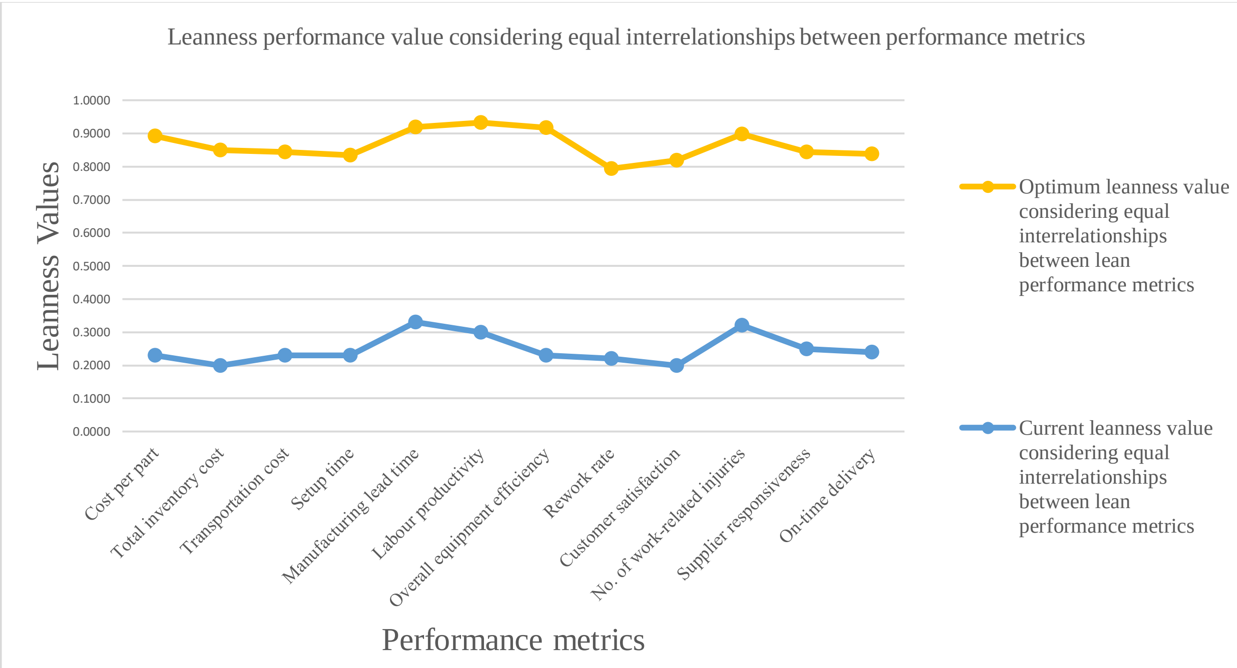

Figure 4.19: Comparison of current and optimum leanness values considering equal interrelationships between performance metrics.

4.8 Discussion

Through this research study, a weighted leanness measurement methodology using fuzzy logic that considers interdependent relationships between performance metrics to provide more accurate leanness score was developed and proposed. This developed measurement approach can be used to assess the effectiveness and efficiency of lean strategies when starting an improvement journey through adapting lean strategies. However, individual lean metrics emphasise specific aspects of the production process. Also, lean strategies can impact some performance metrics positively while having a negative impact on other metrics. For instance, cellular manufacturing principles are used to reduce the amount of time spent on setup activities. However, implementing this strategy can increase the operating cost associated with the adoption of lean strategies.

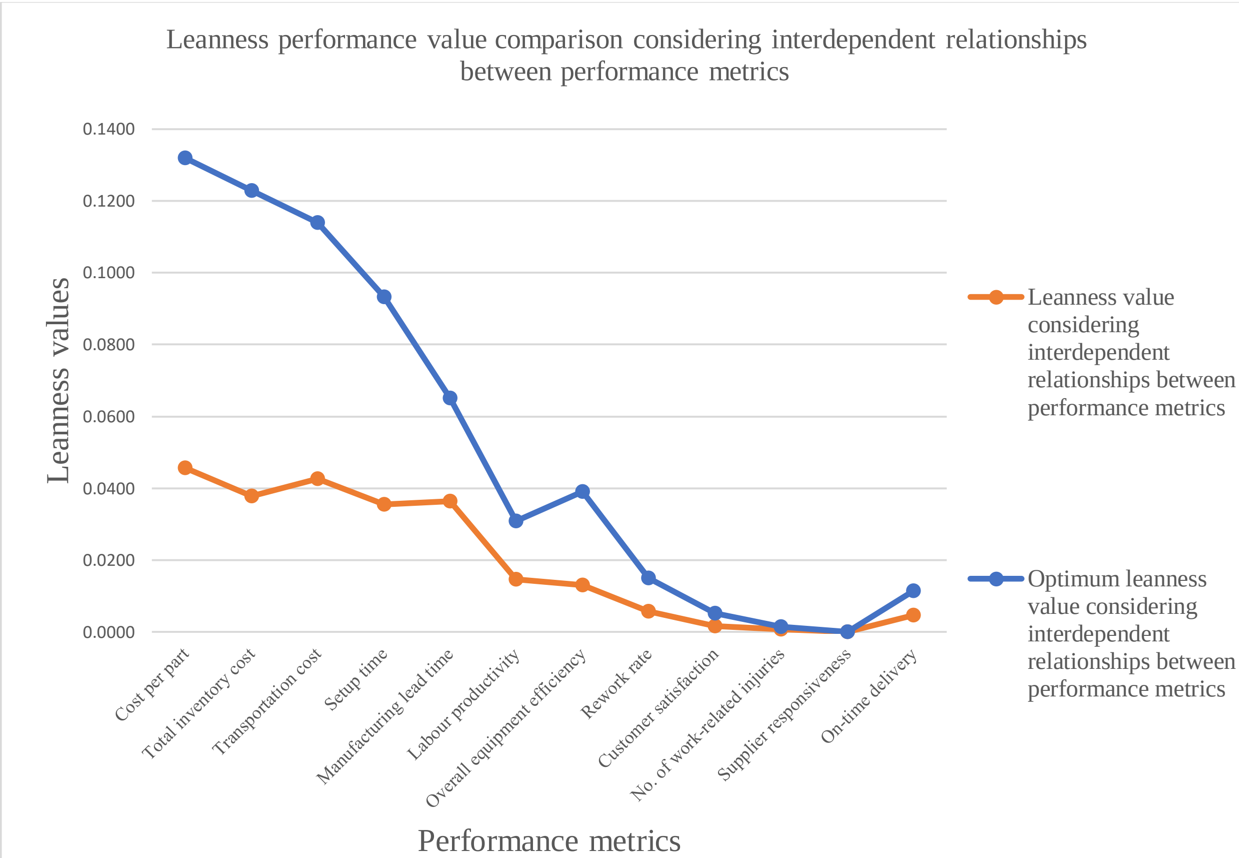

Figure 4.20: Comparison of current and optimum leanness values considering interdependent relationships between performance metrics.

Thus, an integrated leanness index can justify the trade-offs between different lean initiatives and offers an overall leanness index of the production performance. In addition, as mentioned earlier, the selected performance metrics are interrelated with each other and that needs to be considered when measuring the overall leanness of the manufacturing performance. The developed weighted leanness measurement methodology developed in this research study offers a precise integrated approach to measure the overall leanness index of the manufacturing performance based on the interrelationships between performance metrics. This measurement approach is in the complex decision environment based on different opinions and requirements of stakeholders and manufacturers.

The final leanness score provides a more accurate direction for manufacturers to evaluate the lean performance continuously in their improvement program. The overall leanness index in this methodology is the result of the summation of the individual leanness scores of each performance metric (sub-metrics) that considers their relative importance weightings. The proposed weighting method in this research study allows more complex relationships between lean performance measures and performance metrics. The interaction or interrelationships can be controlled through the coupling of phases that comprise the hierarchies of performance measures and performance metrics. The integrated leanness index can be synthesised through the weighted priority of the performance metric through the evaluation of the super-matrix in fuzzy ANP.

Therefore, when analysing and identifying the problematic areas, the worst leanness score can be tracked layer by layer. It should also be considered that the leanness score of the process should be measured and analysed during the implementation of lean strategies to find any irregularities and unsatisfactory progress so managers can identify the problem immediately.

4.9 Validation of proposed methodology through implementation suggested lean initiative

In the previous section, the overall leanness value of Station 4 in the QMC modular construction line considering the interrelationships between lean performance metrics were calculated and found to be 23.87%. Also, it was shown that each performance metric has a lower leanness value compared to its relative optimum leanness value. In the previous chapter, different lean strategies were suggested to enhance the leanness value at Station 4. The lean team suggested JIT, cellular manufacturing, Kanban system, standard work process, SMED, 5S, TPM and production smoothing as appropriate lean tools. These lean strategies can address the identified wastes; (including unnecessary movements, setup time, defects, unnecessary transportation, failure time, WIP, raw materials, final goods inventory and knowledge disconnection) and to improve the selected performance metrics. In this section, the implementation of one lean strategy, 5S, to improve the performance at Station 4 is described. The reason for selecting this lean strategy is mainly because this lean strategy focuses on cleaning and organising the workstation and can involve workers more easily compared to other lean strategies. Also, 5S produces immediate visible results and can motivate the management team as well as the shop floor staff. In addition, implementing 5S principles helps manufacturers to sustain a better-organised workplace to implement other lean strategies, such as standard work and visual management.

4.9.1 Application of one lean initiative in the case study company

After investigating and analysing Station 4, the following steps were introduced to improve the performance at this station:

- Providing more organised inventory systems and bin arrangement
- Eliminating extra materials from the station aisles
- Keeping unneeded items in their locations
- Providing a cleaning check list and performing daily cleaning to ensure the workstation is clean and organised for the next day
- Using a Kanban system to prevent empty bins

The 5S principles were implemented at Station 4 to improve the tools, equipment and inventory management at this station. The checklist for the first three 5S principles was provided considering the condition and specification of Station 4. Also, the operations at this station were observed regularly by the lean team to evaluate the implementation of 5S principles in the manufacturing line.

During the implementation of these principles and observing the operations at this workstation, it was found that the arrangement of bins, baskets and tools improved significantly so the operators performed their tasks more easily. Unorganised equipment and materials, such as gloves and drills, etc. were cleaned and transferred to their place every day by the operators. Finally, rubbish was removed from the workstation and the operators cleaned their workplace on a regular basis. Therefore, the working conditions at Station 4 in the QMC modular line were improved remarkably. In the next section the overall leanness value of this station is calculated after implementing the 5S principles.

4.9.2 Evaluating leanness score before and after lean initiative implementation

After implementing the 5S principles at Station 4 of the QMC modular manufacturing line, the relevant data of performance metrics were measured. The value of performance metrics as well as the leanness values of each metric after implementing the 5S principle are compared with the values before implementing the 5S strategies and are presented in Table 4.14. The graphical comparison of the leanness scores of performance metrics before and after 5S implementation considering the interdependent relationships between performance metrics is shown in Figure 4.21.

After improving the performance at Station 4 in the QMC modular line by implementing 5S principles, the improved overall leanness index was 0.4515 at the HMC modular construction company. This score represents the improvement in the overall leanness score from the previous leanness value of 0.2387 as a result of implementing 5S principles at this station.

Table 4.14 illustrates that the leanness score of most performance metrics increased due to introducing a lean strategy in the manufacturing line. However, there is no significant difference in the leanness score of supplier responsiveness at this workstation after implementing 5S principles. As mentioned in the literature review chapter, 5S principles mainly focus on inventory and tools management at workstations. Therefore, this strategy has less influence on supplier responsiveness. However, implementing 5S impacts some other performance metrics positively such as on-time delivery, manufacturing lead time, setup time, total inventory cost and overall equipment efficiency.

Generally, lean strategies implementation improves the production performance compared to the performance before lean tools implementation. In the case study explained in this chapter, customer satisfaction, overall equipment efficiency and on-time delivery improved significantly and cost per part, total inventory cost, transportation cost and manufacturing lead time were also reduced. This improvement in the production performance can decrease the gap between the existing optimised level for leanness score. Therefore, manufacturers can reduce this gap by implementing further proper lean tools to reduce production wastes and improve the selected performance metrics.

Table 4.14: Leanness values before and after 5S implementation considering the relative importance weightings between lean performance metrics

Performance metric	Relative importance weighting	Metric value before 5S	Leanness value before 5S	Metric value after 5S	Leanness value after 5S
Cost per part (dollars per unit)	0.1989	26690	0.0457	26542.5	0.0954
Total inventory cost (dollars per unit per day)	0.1888	655.40	0.0378	630.55	0.1031
Transportation cost (dollars per unit per day)	0.1853	77.30	0.0426	74.30	0.0832
Setup time (minutes)	0.1544	225.30	0.0355	214.70	0.0661
Manufacturing lead time (hours)	0.1105	9294	0.0365	9155	0.0514
Labour productivity (unit per day)	0.0487	2.65	0.0146	2.75	0.0131
Overall equipment efficiency (%)	0.0567	55.60	0.0130	56.70	0.0160
Rework rate (%)	0.0262	16.40	0.0058	15.30	0.0102
Customer satisfaction (%)	0.0085	45	0.0017	50	0.0023
Number of work-related injuries (accident per day)	0.0026	5	0.0008	4	0.0012
Supplier responsiveness (%)	0.0002	50	0.0001	55	0.0001
On-time delivery (%)	0.0193	55	0.0046	58	0.0063
Overall leanness value			**0.2387**		**0.4515**

Also, determining the interrelationships between each performance metric in the leanness assessment can measure the overall leanness of the organisation more accurately. In the conventional AHP approach, there are two main deficiencies. The first one is using the discrete scale of one to nine in the conventional AHP, which does not consider the uncertainty and ambiguity in the assessment of lean performance measures and performance metrics. There is a high degree of subjective judgement and individual perspectives in determining the relative importance weightings of lean performance measures and performance metrics. Therefore, in this research study, fuzzy triangular numbers are used to deal with the vagueness in individual judgements. In addition, in the AHP approach it is assumed that the performance measures and metrics are independent. However, in the ANP approach, the correlations are treated symmetrically or asymmetrically as appropriate and the interdependencies are captured across and along the hierarchies to determine the relative importance weightings more realistically. Hence, the ANP results of the analysis incorporating the interdependencies are different from the relative importance vector obtained by using the fuzzy AHP method.

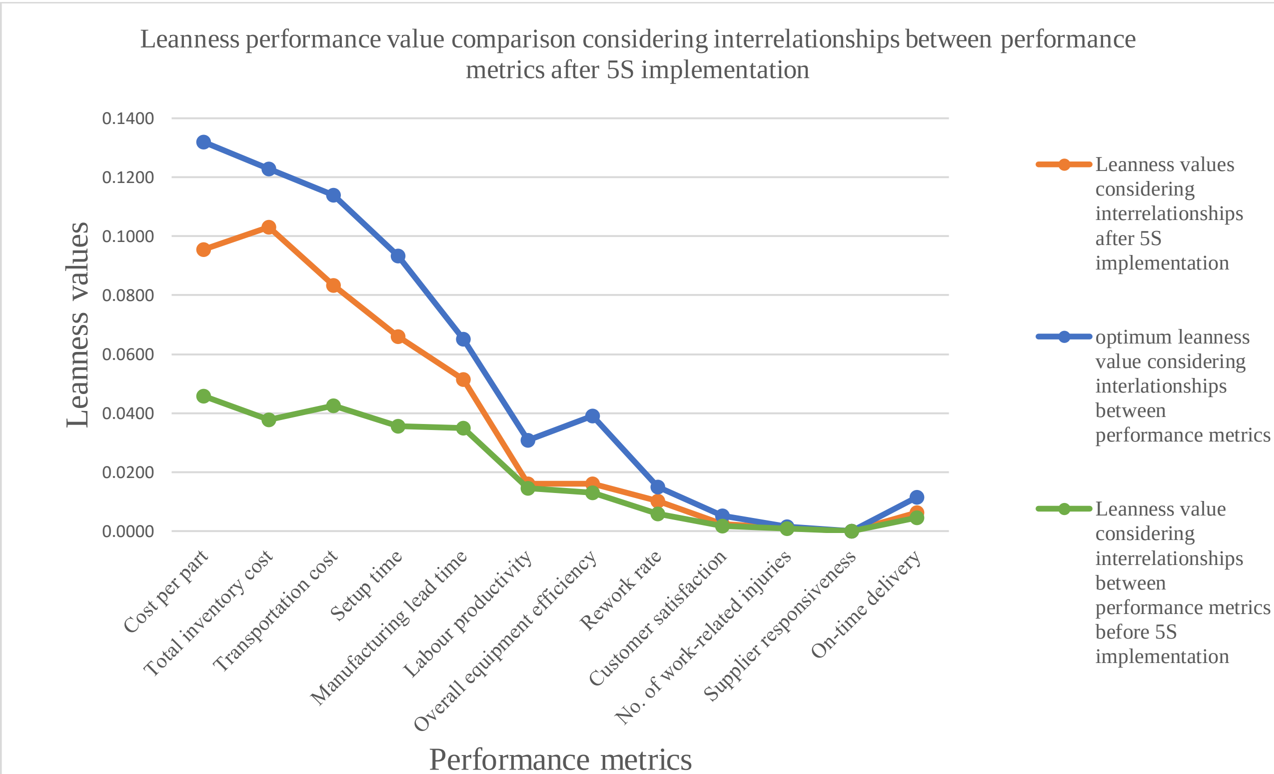

Figure 4.21: Comparison of leanness values before and after 5S implementation considering the interrelationships between lean performance metrics.

However, application of the ANP method has a major difficulty, which is the significant increase in the number of pairwise comparison matrices and pairwise comparison questions required to consider interdependencies among lean performance measures and performance metrics. Despite this difficulty, the fuzzy ANP model can determine more precise analysis by integrating interdependent relationships that are not evident in the other method.

4.10Conclusion

This research study developed and proposed a methodology using the fuzzy set theory to measure an organisation's leanness state more accurately by considering the interdependent relationships between performance metrics. The developed weighted leanness measurement model using fuzzy logic presents a total leanness score that considers the interdependent interrelationships between performance metrics using the fuzzy ANP approach. The new leanness assessment model developed in this research study is useful for managers for decision-making in performance evaluation. The aim of the leanness index is to support the emphasis to sustain a lean culture among employees of the organisation. The fuzzy-ANP methodology is a robust approach in integrating different aspects governing the lean performance of the organisation. The weighted leanness assessment model developed in this research study measures the overall leanness level and considers the relationships between performance metrics as well as their interdependencies across and along the hierarchies. Therefore, this method assesses the overall leanness score of the production performance more accurately by prioritising different performance metrics based on the manufacturer's requirements.

After measuring the leanness, this proposed leanness model defines the optimum leanness level for implementing lean tools to address the identified manufacturing wastes and improve performance metrics. In this research, the fuzzy-ANP methodology is applied to set the leanness goal.

This research validated the proposed weighted leanness measurement methodology to quantify the leanness index of the organisation before and after implementing lean tools considering the interdependent relationships between metrics. The improvement achieved by implementing the 5S principles was analysed using the developed weighted leanness measurement methodology at one workstation at the case study company. The leanness score of Station 4 was found to be 23.87% considering the interdependent relationships between performance metrics. After introducing 5S principles in this workstation, the overall leanness improved and reached 45.15%. In addition, the optimum leanness level at this workstation considering the interrelationships between different performance metrics was found to be 63.05%. Therefore, implementing 5S helps manufacturers to improve the performance toward the optimum leanness score and reduce the gap between the current and optimum leanness levels. Therefore, this research study measures the current and optimum leanness levels of the production performance more accurately by considering the interdependent relationships between performance metrics. This provides a more precise approach for determining leanness performance in the complex decision-making environment that involves different stakeholders with different concerns and requirements.

Chapter 5: Conclusions

This chapter provides a synopsis of the research findings and presents the contribution of this research study to current knowledge. The final section of this chapter outlines the limitations of this study and suggests future research areas.

5.1 Significance of the research project

Lean tools and techniques that have been developed for adopting the lean concept merely focus on making the system leaner and aim to eliminate wastes and reduce variability in the manufacturing system. However, several companies have misapplied lean tools and strategies when transforming into a lean organisation. Misapplication of lean tools can be defined as the implementation of inappropriate lean strategies to solve the problem. In this regard, manufacturers face difficulties in selecting the best set of lean tools to reduce manufacturing wastes and improve performance metrics. Applying inappropriate lean strategies in the production process can increase inefficiencies and non-value-adding activities in the company. Therefore, it is essential to maximise lean implementation benefits within manufacturers' time and budget limitations.

Implementing lean tools and techniques can tackle specific problems in the production systems and achieve visible performance improvement. In this respect, performance metrics are identified to quantify the improvement and justify lean manufacturing implementation. It is vital to quantify the leanness score of a production system to measure the performance and track the efficiencies and effectiveness of lean initiatives. However, individual performance metrics cannot represent the overall leanness of the manufacturing system as they focus on the specific aspect of performance. For instance, quality metrics focus on product quality and on-time delivery, while financial metrics focus on manufacturing and transportation costs. In addition, different performance metrics interrelate with each other, for example, financial metrics are affected by the quality and productivity metrics. Therefore, it is essential to understand performance metrics and determine the interrelationships between these metrics.

Hence, in order to synthesise the various aspect of performance, an integrated measure was developed to consider the interdependent relationships between lean performance measures and performance metrics.

In this research study, the current knowledge of selecting an appropriate set of lean strategies has been advanced through a methodology that considers the impact of lean tools on performance metrics and manufacturing wastes. The proposed selection model illustrated in this study presents the concepts and a systematic methodology to suggest the most appropriate lean strategies for maximising the benefits of lean implementation and determines manufacturers' perceived effectiveness value by reducing wastes and enhancing performance metrics (within budget and time constraints).

In addition, the leanness index is developed to measure the existing level of leanness in the production process and assess an optimum level of leanness. Therefore, this research has developed a weighted fuzzy-based leanness assessment model that considers the interdependent relationships between lean performance metrics to measure the leanness state more accurately. Finally, this research study demonstrates the proposed lean strategies selection model and the leanness assessment models and methodology through their application in a case study company within a real-life industrial context.

5.2 Contribution to the current knowledge

The major accomplishment of this research is the development of a lean strategies selection methodology which considers the relationships of lean tools with the identified performance metrics and manufacturing wastes as well as the development of the weighted leanness assessment model. The contribution of this research to the development and implementation of lean manufacturing is:

- A structured methodology to select the most appropriate and relevant set of lean initiatives for improving selected performance metrics and reducing critical manufacturing wastes within time and budget constraints.

The developed methodology helps manufacturers to select the most appropriate lean initiatives. The selected lean strategies have the highest impacts on critical performance metrics and critical manufacturing wastes. Implementation of the selected lean tools will improve the targeted performance metrics and critical wastes to achieve the highest perceived value.

- Correlation matrices for lean tools and performance metrics, lean tools and manufacturing wastes as a decision-making guideline that represent the effectiveness of the suggested lean strategies to address identified wastes and improve selected performance metrics.
- Development of a fuzzy ANP approach to determine the interdependent relationships between lean performance measures and performance metrics and allocating the relative importance weightings to the selected performance metrics.
- A weighted fuzzy-based leanness assessment model that uses triangular fuzzy numbers and the ANP approach to measure the leanness level of quantitative and qualitative performance metrics considering the interrelationships between lean performance metrics.

The developed weighted leanness assessment model measures the overall leanness score by considering the interdependent relationship between identified performance metrics. The results achieved from the proposed model showed a higher level of accuracy compared to previous methods. Previous research studies assumed that the identified performance metrics do not have an effect on each other. Therefore, equal interrelationships were assumed. The developed methodology in this research considers these interdependent relationships and hence provides a more accurate overall leanness index.

5.3 General conclusions

5.3.1 Development of a methodology for suggesting proper lean initiatives

As mentioned earlier, several manufacturers have failed to achieve the benefits of lean manufacturing and its application mainly due to a lack of knowledge and understanding about lean strategies and their impacts on production performance. As a result of misapplications of lean strategies, inefficiency and non-value-adding activities increase considerably. Currently, existing leanness assessment models lack a systematic approach to consider the impact of lean strategies on the selected performance metrics and identified manufacturing wastes to select an appropriate set of lean tools within the company's resource limitations.

In the proposed model, manufacturers' perception about the complexity of lean strategies implementation and the required and desired level of lean implementation are considered as two important factors to calculate a perceived value index of lean implementation for improving the selected performance metrics and identified manufacturing wastes. These factors also affect the cost and time required to adopt a lean strategy. Therefore, a decision-making function has been developed to identify the most appropriate solution for selecting appropriate lean strategies. This function considers the effects of lean strategies on performance indicators and production problems to maximise the perceived value index based on improving metrics and reducing wastes while minimising the resource consumption of lean implementation.

A real-life case study in a modular construction company was used to validate the effectiveness of the developed methodologies. After defining the scope of this research study, twelve performance metrics and ten manufacturing wastes were identified in the existing production process. Budget and time constraints were allocated by the management team. Based on results obtained from the proposed lean strategies selection, 867 different combinations of lean tools have been generated to eliminate manufacturing wastes and improve performance metrics. However, the perceived value of the best possible scenario of selecting lean tools was 97 (Table 3.7). In this solution, JIT, Kanban system, cellular manufacturing, standard work process, SMED, 5S, TPM and production smoothing were suggested to improve cost per part, transportation cost, setup time, manufacturing lead time, overall equipment efficiency, rework rate and customer satisfaction. The suggested lean tools were selected to address the critical manufacturing wastes: unnecessary movements, setup time, unnecessary transportation, over processing, failure time, final goods, WIP and raw material inventories.

From Table 3.7, it was concluded that implementing Just-In-Time (JIT) can address more manufacturing wastes and improve more performance metrics with the same implementation cost and time. This lean strategy can bring maximum benefits to this company by improving cost per part, total inventory cost, transportation cost, manufacturing lead time and on-time delivery, as well as reducing three manufacturing wastes: finished goods inventories, WIP and raw materials inventory. Then, Kanban systems can reduce three manufacturing wastes: final goods inventory, raw materials inventory and WIP, while improving three performance metrics: total inventory cost, setup time and on-time delivery. Also, cellular manufacturing can improve the performance of the selected workstation at the case study company considerably by improving three performance metrics: transportation cost, manufacturing lead time and labour productivity while addressing two manufacturing wastes: unnecessary movements and transportation. In addition, 5S principles can improve four performance metrics: transportation cost, labour productivity, number of work-related injuries and on-time delivery while reducing one manufacturing waste: unnecessary movements at the workstation. Standard work process, SMED, total productive maintenance, and production smoothing are the other suggested lean strategies in the scope of this study. Therefore, the suggested sequence of implementing lean strategies in this company is:

Table 3.8 illustrates the budget and time required for implementing the suggested lean tools and the budget and time constraints allocated by the manufacturer. From this table, it can be seen that there are slack values between the allocated resource constraints and the actual resources required.

5.3.2 Decision making in a dynamic situation

The manufacturing performance is affected by internal and external factors of the organisation. Therefore, manufacturers are always faced with challenges to deal with fluctuations in the production process. Thus, the proposed method for selecting lean strategies can be applied in a dynamic situation and it can facilitate the decision-making process by changing the input variables. In this research, transportation cost and setup time were the most critical performance metrics while unnecessary movements and transportation were the most critical manufacturing wastes. However, the situation changed and the management team decided to choose total inventory cost as their critical performance metric and WIP and raw materials inventory as the critical manufacturing wastes. The manufacturer also decided to change the budget and time allocation for implementing lean strategies. The results from the MATLAB program for the new problem identified 664 possible combinations of lean strategies that have high impacts on critical performance metrics and manufacturing wastes.

The best combination of lean strategies targets six performance metrics: cost per part, total inventory cost, manufacturing lead time, overall equipment efficiency, rework rate and customer satisfaction, along with seven manufacturing wastes: unnecessary movements, unnecessary transportation, defects, over-processing, WIP, raw materials inventory and knowledge disconnection (Table 3.9). The manufacturer's perceived effectiveness value of the optimum solution for the new problem is 79 within the new cost and time limitations. Therefore, the set of suggested lean strategies are JIT, TQM, Kanban system, standard work process, cellular manufacturing, and information flow management system. Manufacturers can use the proposed model to make an appropriate decision. In the proposed lean strategies selection model and methodology, managers can identify the optimum set of lean tools according to relationships with performance metrics and manufacturing wastes.

5.3.3 Development of the weighted leanness measurement methodology

In the current literature, either qualitative measures (Vinodh & Chintha 2010; Vinodh & Balaji 2011; Vinodh & Chintha 2011; Vimal & Vinodh 2012) or quantitative measures (Wan & Chen 2008) are considered to measure the leanness of manufacturing performance. Few researchers attempted studies to provide an integrated leanness index to reflect the overall performance of the manufacturing line (Amin 2012; Wong et al. 2012). However, in their methods, the interrelationships between lean performance metrics were not determined to measure the overall leanness of the production performance. In this study, the interrelationships were established and considered.

5.3.4 Fuzzy ANP approach to allocate relative importance weightings to performance metrics

This research study utilised fuzzy ANP methods to integrate different dimensions governing the organisation's performance. In addition, fuzzy logic has been used to deal with vagueness and ambiguities in the decision makers' perception and judgments and analyse the qualitative variables. The ANP is a robust technique to offer a more precise and accurate analysis by integrating interdependent relationships between lean performance metrics across and along the hierarchies. In this method, pairwise comparison matrices are established between lean performance measures with respect to the overall goal of lean implementation, between performance metrics with respect to each performance measure, between lean performance measures with respect to each measure and, finally, between performance metrics with respect to each metric. Therefore, interdependent relationships are analysed more accurately to determine and allocate more precise relative importance weightings to each performance metric. However, this method requires more time and resources compared to conventional AHP. In the proposed fuzzy ANP model, the lean performance measures and performance metrics linguistic evaluation are converted into triangular fuzzy numbers to establish pairwise comparison matrices and determine the relative importance weightings of the selected performance metrics.

This research advances the fuzzy-based leanness assessment model by allocating the relative importance weightings to performance metrics and develops the weighted leanness assessment model using fuzzy set theory, which prioritises performance metrics per manufacturer's requirements. In the proposed leanness evaluation model, both qualitative and quantitative performance metrics are considered to quantify and justify improvements achieved through lean implementation. The optimum leanness level is measured by considering the interrelationships between lean performance metrics to compare the gap between the current leanness state and the optimum leanness level. This method can help manufacturers to evaluate the effectiveness of implementing lean tools and techniques and identify the problematic areas related to lean implementation. However, lean manufacturing is a continuous improvement approach, hence, after achieving the optimum leanness goal, manufacturers can revise the leanness goal in the manufacturing process.

A real life case study was used to show the effectiveness and validate the weighted leanness evaluation methodology. Table 4.13 shows the leanness level of the selected production line considering equal relationships and unequal relationships between lean performance metrics as well as optimum leanness level. From this table, financial performance metrics have high relative importance weightings in this company and among them, cost per part has the highest weighting value. In addition, Table 4.13 shows that the existing leanness index is 0.2387 (23.87%) and the optimum leanness score is 0.6305 (63.05%) in the selected workstation. Table 4.14 demonstrates the leanness level of the selected workstation before and after implementing the 5S principles. This table clearly indicates the negative and positive results of applying the 5S principles. This table shows an improvement that reaches 0.4515 (45.15%) in the overall leanness score of the selected workstation after adopting the 5S principles. However, an optimum leanness score of 0.6305 (63.05%) can be reached by implementing further appropriate lean strategies.

As lean manufacturing is a continuous improvement approach, consistent implementation of lean strategies to improve the production process can reduce the variation between the value of raw data. Less variation in the raw data values leads to less stiffness in the shape of fuzzy numbers and consequently means better production performance. Therefore, smaller differences between consecutive data generate better lean ranges and enhance the overall performance of the production process. Finally, this research developed the weighted leanness measurement methodology using the fuzzy theory that measures the overall leanness of the production process by considering the interdependent relationships between identified lean performance metrics, which can provide a meaningful and more accurate integrated leanness index.

5.4 Limitation of the study and future directions

This research study has made a major contribution towards an understanding of lean manufacturing and the application of lean strategies and techniques. However, there are some limitations to this research:

- The guidelines for calculating the perceived value of lean implementation are provided as Appendix A. In this research, these values are predicted due to difficulty in determining the perceived effectiveness value before implementing the lean strategies.
- It was assumed that implementing one lean strategy does not affect the implementation of other lean strategies.
- The probability of failure to calculate the risk cost of implementing lean strategies is difficult to specify and can be predicted based on past experiences with similar situations.

Therefore, there might be some inaccuracies in calculating the risk cost associated with lean strategies implementation.

- In this research study, only a few lean strategies, performance metrics and manufacturing wastes were considered. Implementing more lean tools and identifying more performance metrics and manufacturing wastes can improve the results of the lean strategies selection method.
- In this research study, fuzzy triangular numbers were used to determine the relative importance weightings among performance metrics and to measure the leanness score of each metric. However, triangular fuzzy numbers may not be suitable and applicable for all industrial applications.

Based on the research findings and outcomes, the proposed models and methodology in this research can be further enhanced in the following areas:

- The correlation between lean strategies, performance metrics and manufacturing wastes needs to be investigated and verified using information available in the organisations that implemented lean strategies.
- Examining the effects of forced changes of lean strategies implementation on the overall performance of a manufacturing process can be a further extension of this research.
- Future research must determine the correct fuzzy numbers for particular applications in the ANP approach. Further research is required for identifying more accurate fuzzy numbers in the fuzzy ANP approach in various applications and industries.
- Estimating the risk cost associated with lean implementation requires more information on failure from the field. Therefore, more information should be obtained to predict the risk cost of lean implementation more accurately.
- More real-life case studies to validate the proposed models and methodologies can provide a further extension of this research.

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Appendices

Appendix A

Table A. 1: Level of lean implementation

Rating	Level of lean implementation	Description
0	No implementation	No lean strategies are selected for implementation.
1	Basic	The selected lean strategies are easy to design and adapt with the current production process and need low or very low implementation cost (operating, amortisation, variable and risk cost) and time (planning, training, development and validation time).
2	Moderate	The selected lean strategies require a moderate effort to improve the existing production process and need a moderate level of cost and time for implementation.
3	Comprehensive	The selected lean strategies require a high level of cost and time to be able to design and adopt into the existing manufacturing process.

Table A. 2: Complexity level of lean implementation

Rating	Manufacturing process complexity level	Description
1	Low complexity	Very basic operation and easy to implement lean strategies.
2	Medium complexity	Production process has a medium level of complexity and requires moderate effort, cost and time resources to improve the production process by implementing lean strategies.
3	High complexity	The manufacturing operations have a high level of complexity and require a high level of effort to implement lean strategies.

Table A. 3: Perceived value level of improving performance metrics

Rating	Value level of improving performance metrics	Description
0-1	Insignificant	Improving the selected performance metric is insignificant for the manufacturer.
2-4	Low	Improving the selected performance metric has a minor impact on the production process.
5-7	Medium	Improving the selected performance metric has a medium impact on the production process.
8-10	Significant	Improving the selected performance metric is the most significant target for the manufacturer.

Table A. 4: Perceived value level of reducing wastes

Rating	Value level of reducing wastes	Description
0-1	Insignificant	Reducing the selected waste is insignificant for the manufacturer.
2-4	Low	Reducing the selected waste has a minor impact on the production process.
5-7	Medium	Reducing the selected waste has a medium impact on the production process.
8-10	Significant	Reducing the selected waste is the most significant target for the manufacturer.

Table A. 5: Operating cost level

Rating	Operating cost level	Description
0	No cost	Implementing these lean strategies requires no extra operating cost.
1	Low operating cost	The existing manufacturing system has adequate facilities to implement lean strategies and requires a low level of operating cost to improve the production process.
2	Medium operating cost	The existing manufacturing system has some facilities to implement lean strategies and requires a medium level of operating cost to improve the production process.
3	High operating cost	Significant amount of operating cost required to implement lean strategies

Table A. 6: Amortisation cost level

Rating	Amortisation cost level	Description
0	No cost	Implementing these lean strategies requires no extra amortisation cost.
1	Low amortisation cost	The existing manufacturing system has adequate facilities to implement lean strategies and requires a low level of amortisation cost to improve the production process.
2	Medium amortisation cost	The existing manufacturing system has some facilities to implement lean strategies and requires a medium level of amortisation cost to improve the production process.
3	High amortisation cost	Significant amount of amortisation cost required to implement lean strategies.

Table A. 7: Variable cost level

Rating	Variable cost level	Description
0	No cost	Implementing these lean strategies requires no extra variable cost.
1	Low variable cost	The existing manufacturing system has adequate facilities to implement lean strategies and requires a low level of variable cost to improve the production process.
2	Medium variable cost	The existing manufacturing system has some facilities to implement lean strategies and requires a medium level of variable cost to improve the production process.
3	High variable cost	Significant amount of variable cost required to implement lean strategies.

Table A. 8: Risk cost level

Rating	Risk cost level	Description
0	No change	The existing manufacturing operations and activities is used and no additional risk is involved
1	Low Risk	Most of the existing manufacturing operations and activities is used and corresponds to low change level. Therefore, low risk level is involved.
2	Medium Risk	Some of the existing manufacturing operations and activities is used and corresponds to medium change level. Therefore, medium risk level is involved.
3	High Risk	Corresponds to complete changes in the manufacturing line. Almost a new design is required and any previous activities and operations is hardly reusable. Therefore, high risk level is involved.

Table A. 9: Risk level due failure probability due to lean implementation

Rating	Risk level	Description
1	Low	Requires few refinements in the existing production system, no change in mode of failure
2	Medium	Requires moderate amendments in the existing production system but still no additional mode of failure
4	High	Requires significant changes in the existing production system and new mode of failure is introduced due to changes in the manufacturing system

Table A. 10: Planning time level

Rating	Planning time level	Description
0	No time	Implementing these lean strategies requires no extra planning time to improve the existing manufacturing process.
1	Low planning time	Implementing these lean strategies requires a minimum amount of planning time to improve the existing manufacturing process.
2	Medium planning time	Implementing these lean strategies requires some extra planning time to improve the existing manufacturing process.
3	High planning time	Implementing these lean strategies requires a significant amount of planning time to improve the existing manufacturing process.

Table A. 11: Training time level

Rating	Training time level	Description
0	No time	Implementing these lean strategies requires no extra training time to improve the existing manufacturing process.
1	Low training time	Implementing these lean strategies requires a minimum amount of training time to improve the existing manufacturing process.
2	Medium training time	Implementing these lean strategies requires some extra training time to improve the existing manufacturing process.
3	High training time	Implementing these lean strategies requires a significant amount of training time to improve the existing manufacturing process.

Table A. 12: Development time level

Rating	Development time level	Description
0	No time	Implementing these lean strategies requires no extra development time to improve the existing manufacturing process.
1	Low development time	Implementing these lean strategies requires a minimum amount of development time to improve the existing manufacturing process.
2	Medium development time	Implementing these lean strategies requires some extra development time to improve the existing manufacturing process.
3	High development time	Implementing these lean strategies requires a significant amount of development time to improve the existing manufacturing process.

Table A. 13: Validation time level

Rating	Validation time level	Description
0	No time	Implementing these lean strategies requires no extra validation time to improve the existing manufacturing process.
1	Low validation time	Implementing these lean strategies requires a minimum amount of validation time to improve the existing manufacturing process.
2	Medium validation time	Implementing these lean strategies requires some extra validation time to improve the existing manufacturing process.
3	High validation time	Implementing these lean strategies requires a significant amount of validation time to improve the existing manufacturing process.

Appendix B

Table B. 1: Lean performance measures and performance metrics and their lean manufacturing behaviours (Allen et al. 2001; Agarwal et al. 2006; Dennis & Shook 2007; Ramesh & Kodali 2012)

Performance measure	Performance metric	Quant.	Qualit.	Metric behaviour	Definition
Financial	Cost per part	x		Negative	The total cost per unit for raw materials inventories, including processing and indirect overheads.
	Total inventory cost	x		Negative	The total cost related to different kinds of inventories including final goods inventory, WIP and raw materials inventory.
	Transportation cost	x		Negative	The total cost of transporting the product to the final customer.
	Raw material variance	x		Negative	Compares the total raw materials consumption to the standard quantity per part multiplied by the total parts produced. This will provide a variance to the standard. Multiplying the variance to the standard by the average cost of raw materials, the variance in terms of cost will be obtained. High variance can be the result of over-processing, high rate of scrap or material wastage.
Productivity	Kanban waiting time	x		Negative	Wait Kanban Time mode is the status of the line when the order is waiting to resume making the desired products of the customer. High amount of Wait Kanban Time shows lack of balance between operations as a result of greater capacity than required to meet the demand.
	Manufacturing lead time	x		Negative	The period of time when the manufacturing process of an order is started until the order is ready to be delivered to the customer.

Performance measure	Performance metric	Quant.	Qualit.	Metric behaviour	Definition
	Labour productivity	x		Positive	The ratio of monthly value of products shipped to the monthly expenditures of workers.
	Total parts produced	x		Positive	Comparing all measurements, including yield or scrap rate to the total parts produced and presented as a percentage of this metric.
	Equipment downtime	x		Negative	Expressed as the percentage of time that the machine is unable to produce products during the scheduled manufacturing time.
	Shorting customer process	x		Negative	Can be measured by dividing the amount of stop time by standard operation time, excluding the Wait Kanban Time.
	Setup time	x		Negative	The period of time from the last good of one part to the first good of another part type is measured in minutes and expressed as the setup time.
	Overall equipment efficiency (OEE)	x		Positive	Determining the productivity at the equipment level.
Quality	Customer satisfaction		x	Positive	The number of defective parts rejected from the following process/ customer. Customer satisfaction is expressed as a percentage of the total parts produced by a process.
	Reject rate	x		Negative	The percentage of products produced from raw materials to those that require reworking at least once in the process.
	Rework rate	x		Negative	The percentage of products produced from raw materials to those that require reworking at least once in the process.
	Yield	x		Positive	The percentage of total parts produced that are accepted without any rework.

Performance measure	Performance metric	Quant.	Qualit.	Metric behaviour	Definition
Flexibility	Missed delivery cycled	x		Negative	Evaluates the efficiency of material handlers in a pull-based manufacturing process. Failure to complete a delivery cycle leads to fluctuation in the material process. Therefore, the customer's process cannot have adequate parts to continue the production process.
	Level of technology usage		x	Positive	The level of technology used for the particular process.
	On-time delivery	x		Positive	The percentage of products produced that meet the customers' deadline.
	Supplier responsiveness		x	Positive	The number of times that suppliers deliver the required raw materials on time to the manufacturer.
	Quick response to customer	x		Positive	The ability of the production process to meet variation in customer demand.
Health and safety	Number of work-related injuries	x		Negative	Work-related injuries are divided into two categories: • Accidents and sudden injuries such as cuts and contusions • Cumulative trauma disorders or repetitive motion injuries such as carpel tunnel syndrome
	Lost work days	x		Negative	Production downtime as a result of work-related injuries of employees and/or health and safety issues.
	Number of medical visits	x		Negative	Number of times that employees visit a medical facility.
	Word-related restrictions	x		Negative	Number of work-related restrictions resulting from the production environment in the manufacturing line.
Morale	Employment security		x	Positive	The aim of lean manufacturing is not to eliminate jobs in the organisation but to involve labourers in the improvement activities. Therefore, the number of employment contracts

Performance measure	Performance metric	Quant.	Qualit.	Metric behaviour	Definition
					terminated in a certain period of time is a measure to evaluate the job security of the organisation.
	Culture		x	Positive	The culture quality in the lean manufacturing environment depends on the visual management, standardisation and teamwork, etc. A Likert scale-based questionnaire is the appropriate method to measure the quality of culture in the organisation because this metric is a qualitative measure.
	Governance		x	Positive	Governance is defined by how a team is organised, functions and behaves. The quality of governance is a critical measure of team morale and can be quantify by a Likert scale-based questionnaire.
	Employee involvement		x	Positive	This metric is measured by the number of all types of activity in which an average employee may be involved, such as the number of Kaizen circles.
	Employee training and development		x	Positive	The number of training and development programmes for employees undertaken in the organisation.

Appendix C

Table C. 1: Suggested lean techniques for identified performance metrics

Perceived effectiveness value	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	Number of work-related injuries	Supplier responsiveness	On-time delivery
47	1	0	1	1	1	0	1	1	1	0	0	0

The complete results obtained for this section is available on request.

Appendix D

Table D. 1: Suggested lean techniques for identified manufacturing wastes

Perceived value effectiveness	Unnecessary movements	Setup time	Defects	Unnecessary transportation	Final goods inventory	Over processing	Failure time	WIP	Raw materials inventory	Knowledge disconnection
47	1	1	1	1	1	1	1	0	0	0

The complete results obtained for this section is available on request.

Appendix E

Table E. 1: Suggested lean techniques based on performance metrics in dynamic situation

Perceived value	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	OEE	Rework rate	Customer satisfaction	Number of work-related injuries	Supplier responsiveness	On-time delivery
38	1	1	0	0	1	0	1	1	1	0	0	0

The complete results obtained for this section is available on request.

Appendix F

Table F. 1: Suggested lean techniques for identified manufacturing wastes in dynamic situation

Perceived value effectiveness	Unnecessary movements	Setup time	Defects	Unnecessary transportation	Final goods inventory	Over processing	Failure time	WIP	Raw materials inventory	Knowledge disconnection
41	1	0	1	1	0	1	0	1	1	1

The complete results obtained for this section is available on request.

Appendix G

The MATLAB programming code for the lean strategies selection method

MATLAB code for establishing the relationship between lean tools, performance metrics and manufacturing wastes

```
% Establishing 3D matrix for correlation among lean tools, manufacturing
% wastes and performance metrics
% FS:5S
% TPM: Total Productive Maintenance
% JIT: Just-In-time
% TQM: Total Quality Management
% Kanban: Pull-Kanban system
% PSmoothing: Production Smoothing
% SWK: Standard Work process
% VMS: Visual Management system
% Cellular: Cellular Manufacturing
% SMED: Single Minute Exchange of Die
% SIP: Safety improvement program
% IFMS: Information flow management system

% importing the interrelationships of  metrics VS. Wastes for each lean tools
FS=xlsread('3D Matrix','5S');
TPM=xlsread('3D Matrix','TPM');
JIT=xlsread('3D Matrix','JIT');
TQM=xlsread('3D Matrix','TQM');
Kanban=xlsread('3D Matrix','Pull-Kanban system');
PSmoothing=xlsread('3D Matrix','Production Smoothing');
SWK=xlsread('3D Matrix','Standard Work Process');
VMS=xlsread('3D Matrix','Visual Management System');
Cellular=xlsread('3D Matrix','Cellular Manufacturing');
SMED=xlsread('3D Matrix','SMED');
SIP=xlsread('3D Matrix','Safety improvement program');
IFMS=xlsread('3D Matrix','Information flow management sys');

% Making 3D Matrix
% First dimension is metrics
% Second dimension is wastes
% Third dimension is tools
A=cat(3,Cellular,FS,IFMS,JIT,Kanban,PSmoothing,SIP,SMED,SWK,TPM,TQM,VMS)

% Choose metrics and wastes and determine which tools should be used (which
% tools have values of 3)
metrics = [3 5 6];
wastes = [1 8];
A(metrics,wastes,:)
```

```
usetool = zeros(1,size(A,3));
for k = 1:size(A,3)
    if any(any(A(metrics,wastes,k) == 3))
        usetool(k) = 1;
    end
end
usetool
toolsToBeUsed = find(usetool)
```

MATLAB code for finding the best lean strategies based on their impacts on performance metrics and manufacturing wastes:

```
function [perceive,b]=LPM_C_T_Wastes_Metrics2

timeandcostcalculation=zeros(12,8);
checkmatrix=zeros(1,7);
perceive=zeros(1,13);
combi=zeros(1,11);

timeandcostmatrix=[3 3 2 3 4 2 3 3
9 7 3 2 9 3 4 4
8 4 3 7 6 5 8 4
8 4 4 3 5 4 6 4
7 7 4 3 6 6 5 5
6 2 2 5 4 5 4 2
5 1 2 6 3 4 2 3
6 6 3 3 6 6 5 3
8 5 2 4 8 7 4 4
6 4 2 5 6 6 4 4
7 3 2 2 4 3 4 2
5 9 3 1 9 8 6 4];

constraintmatrix=[50 40 45 50 55 45 35 50];
pervalmetrics=[4 5 9 9 7 5 8 5 5 3 4 7];
pervalwastes=[9 7 5 9 5 7 5 4 4 3];

n=1023;
choosenmetrics=zeros(1,12);
rval=zeros(1,10);
m=1;
c=1;
while n>0
    n1=de2bi(n,12);
    k1=de2bi(n,10);
    for i=1:12
        choosenmetrics(1,i)=n1(1,i);
    end
    for i=1:10
```

```
    rval(1,i)=k1(1,i);
  end

  matr = zeros(12,10);
  relationshipmatrix=zeros(12,12);

  if choosenmetrics(1,1)==1 %%for varing the matrix
    relationshipmatrix(3,1)=1;
    relationshipmatrix(7,1)=1;
  end
  if choosenmetrics(1,2)==1
    relationshipmatrix(3,2)=1;
    relationshipmatrix(5,2)=1;
    relationshipmatrix(12,2)=1;
  end
  if choosenmetrics(1,3)==1
    relationshipmatrix(1,3)=1;
    relationshipmatrix(3,3)=1;
    relationshipmatrix(9,3)=1;
  end
  if choosenmetrics(1,4)==1
    relationshipmatrix(5,4)=1;
    relationshipmatrix(10,4)=1;
  end
  if choosenmetrics(1,5)==1
   relationshipmatrix(3,5)=1;
   relationshipmatrix(9,5)=1;
   relationshipmatrix(12,5)=1;
  end
  if choosenmetrics(1,6)==1
    relationshipmatrix(1,6)=1;
    relationshipmatrix(9,6)=1;
  end
  if choosenmetrics(1,7)==1
    relationshipmatrix(2,7)=1;
  end
  if choosenmetrics(1,8)==1
    relationshipmatrix(4,8)=1;
    relationshipmatrix(6,8)=1;
  end
  if choosenmetrics(1,9)==1
    relationshipmatrix(4,9)=1;
    relationshipmatrix(7,9)=1;
  end
  if choosenmetrics(1,10)==1
    relationshipmatrix(1,10)=1;
    relationshipmatrix(11,10)=1;
  end
  if choosenmetrics(1,11)==1
    relationshipmatrix(12,11)=1;
```

```
end
if choosenmetrics(1,12)==1
   relationshipmatrix(1,12)=1;
   relationshipmatrix(3,12)=1;
   relationshipmatrix(5,12)=1;
end

if rval(1,1)==1
   matr(1,1)=1;
   matr(8:9,1)=1;
end
if rval(1,2)==1
   matr(10,2)=1;
end
if rval(1,3)==1
   matr(4,3)=1;
end
if rval(1,4)==1
   matr(9,4)=1;
end
if rval(1,5)==1
   matr(3,5)=1;
   matr(5:6,5)=1;
end
if rval(1,6)==1
   matr(7,6)=1;%%
end
if rval(1,7)==1
   matr(2,7)=1;
   matr(11,7)=1;
end
if rval(1,8)==1
   matr(3,8)=1;
   matr(5,8)=1;
   matr(9,8)=1;
end
if rval(1,9)==1;
   matr(3,9)=1;
   matr(5,9)=1;
end
if rval(1,10)==1;
   matr(12,10)=1;
end %%finish varing matrix

matrixsum=sum(relationshipmatrix,2);
matx=sum(matr,2);
for i=1:12
   if matrixsum(i,1)>=1
      matrixsum(i,1)=1;
   else
```

```
        matrixsum(i,1)=0;
    end
     if matx(i,1)>=1
        matx(i,1)=1;
    else
        matx(i,1)=0;
    end
end

leantools=zeros(12,1);
for i=1:12
    if matrixsum(i,1)==1&& matx(i,1)==1
        leantools(i,1)=1;
    else
        leantools(i,1)=0;
    end
end


for i=1:12
    timeandcostcalculation(i,1)=leantools(i,1)*timeandcostmatrix(i,1);
    timeandcostcalculation(i,2)=leantools(i,1)*timeandcostmatrix(i,2);
    timeandcostcalculation(i,3)=leantools(i,1)*timeandcostmatrix(i,3);
    timeandcostcalculation(i,4)=leantools(i,1)*timeandcostmatrix(i,4);
    timeandcostcalculation(i,5)=leantools(i,1)*timeandcostmatrix(i,5);
    timeandcostcalculation(i,6)=leantools(i,1)*timeandcostmatrix(i,6);
    timeandcostcalculation(i,7)=leantools(i,1)*timeandcostmatrix(i,7);
    timeandcostcalculation(i,8)=leantools(i,1)*timeandcostmatrix(i,8);
end

costandtimesum=sum(timeandcostcalculation);

for j=1:8
    if costandtimesum(1,j)>constraintmatrix(1,j)
        checkmatrix(1,j)=0;
    else
        checkmatrix(1,j)=1;
    end

end
check1=sum(checkmatrix);

if check1==8
    totalperceivedvalue=sum(relationshipmatrix); %Perceived value sum
    for i=1:12
        perceive(m,i+1)=choosenmetrics(1,i);

        if totalperceivedvalue(1,i)>0
            totalperceivedvalue(1,i)=pervalmetrics(1,i);
        else
```

```
                totalperceivedvalue(1,i)=0;
            end
        end
              perceive(m,1)=sum(totalperceivedvalue);
              m=m+1;
    end
    result=perceive;

     if check1==8
       maty=sum(matr); %Perceived value sum
       for i=1:10
            combi(c,i+1)=rval(1,i);
            if maty(1,i)>0
                maty(1,i)=pervalwastes(1,i);
            else
                maty(1,i)=0;
            end
        end
              combi(c,1)=sum(maty);
              c=c+1;

     end

    comb=combi;
    x=n;
    y=perceive(m,1);
    plot(x,y)
    n=n-1;


end


[maxval,maxloc]=max(result);
maxresult=result(maxloc(1,1),:);
sortresult=sortrows(result);
[maxvalue,maxlocation]=max(comb);
maxcomb=comb(maxlocation(1,1),:);
sortcomb=sortrows(comb);
xlswrite('LPM_C_T_Wastes_Metrics2.xlsx',sortresult,'result','A3');
xlswrite('LPM_C_T_Wastes_Metrics2.xlsx',maxresult,'result','A2');
xlswrite('LPM_C_T_Wastes_Metrics2.xlsx',sortcomb,'comb','A3');
xlswrite('LPM_C_T_Wastes_Metrics2.xlsx',maxcomb,'comb','A2');
% comb
% result

end
```

Appendix H

MATLAB code for measuring the overall leanness index using the weighted leanness assessment model

MATLAB code for calculating the interdependent relationship between lean performance metrics using Fuzzy ANP:

```
%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','1','B2:F6');

% Create output variable
relationship1 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};
fuzzyrelationshipcell1={};
[m n]=size(relationship1);
for i=1:m
    for j=i+1:m
      relationship1(j,i) = 1 / relationship1(i,j);
    end
end

for i=1:m
    for j=1:n
        criteria1=relationship1(i,j);
        if criteria1>=1
            fuzzyrelationshipcell1{i,j}=FuzzyTFN{criteria1, 1};
        else
            fuzzyrelationshipcell1{i,j}=FuzzyTFN{round(criteria1^-1),2};
        end
    end
end

for i=1:m
    vec=[fuzzyrelationshipcell1{i,:}];
    extendedm{1,i}=sum(reshape(vec,3,[]),2);
end
```

```
vec=[extendedm{1,:}];
sumextedendm=sum(reshape(vec,3,[]),2)';

for i=1:m
    vec=[extendedm{1,i}]';
    for j=1:3
        value=sumextedendm(1,4-j);

        sumvalue(1,j)=(vec(1,j))*(1/value);
    end
    extendedm{1,i}=sumvalue;
end

% degree of possibility calculation
%             /---
%             | 1    if m2>=m1
%             |
%             | 0    if l1>=l2
% V(M2>=M1) = <
%             |     l1-u2
%             | --------------- otherwise
%             | (m1-u2)-(m1-l1)


degreeofpossibility1=zeros(m*(m-1),3);
c = 1;

for i=1:m
    for j=1:m
        if i~=j
            degreeofpossibility1(c,[1 2]) = [i j];
            M1 = extendedm{1,i};
            M2 = extendedm{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility1(c,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility1(c,3) = 0;
            else
                degreeofpossibility1(c,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            c=c+1;
        end
    end
end

weights = zeros(1,m);
for i=1:m,
    weights(1,i) = min(degreeofpossibility1([find(degreeofpossibility1(:,1) == i)], [3]));
end
W1=weights/sum(weights)
```

```
%%
%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Financial','B2:M13');

% Create output variable
relationship21 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;
%
FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};
fuzzyrelationshipcell21={};
[a b]=size(relationship21);
for i=1:a
    for j=i+1:a
      relationship21(j,i) = 1 / relationship21(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria21=relationship21(i,j);
        if criteria21>=1
            fuzzyrelationshipcell21{i,j}=FuzzyTFN{round(criteria21), 1};
        else
            fuzzyrelationshipcell21{i,j}=FuzzyTFN{round(criteria21^-1),2};
        end
    end
end

for i=1:a
    vec21=[fuzzyrelationshipcell21{i,:}];
    extendedm21{1,i}=sum(reshape(vec21,3,[]),2);
end

vec21=[extendedm21{1,:}];
sumextedendm21=sum(reshape(vec21,3,[]),2)';

for i=1:a
    vec21=[extendedm21{1,i}]';
    for j=1:3
        value=sumextedendm21(1,4-j);

        sumvalue(1,j)=(vec21(1,j))*(1/value);
    end
    extendedm21{1,i}=sumvalue;
```

```
end
%
% degree of possibility calculation
%              /---
%              | 1    if m2>=m1
%              |
%              | 0    if l1>=l2
% V(M2>=M1) = <
%              |     l1-u2
%              | --------------- otherwise
%              | (m1-u2)-(m1-l1)


degreeofpossibility21=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility21(g,[1 2]) = [i j];
            M1 = extendedm21{1,i};
            M2 = extendedm21{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility21(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility21(g,3) = 0;
            else
                degreeofpossibility21(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
%%
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility21([find(degreeofpossibility21(:,1) == i)], [3]));
end
weights21=weights/sum(weights);

%%
%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Productivity','B2:M13');

% Create output variable
relationship22 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
```

```
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};
fuzzyrelationshipcell22={};
[a b]=size(relationship22);
for i=1:a
    for j=i+1:a
      relationship22(j,i) = 1 / relationship22(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria22=relationship22(i,j);
        if criteria22>=1
            fuzzyrelationshipcell22{i,j}=FuzzyTFN{criteria22, 1};
        else
            fuzzyrelationshipcell22{i,j}=FuzzyTFN{round(criteria22^-1),2};
        end
    end
end

for i=1:a
    vec22=[fuzzyrelationshipcell22{i,:}];
    extendedm22{1,i}=sum(reshape(vec22,3,[]),2);
end

vec22=[extendedm22{1,:}];
sumextedendm22=sum(reshape(vec22,3,[]),2)';

for i=1:a
    vec22=[extendedm22{1,i}]';
    for j=1:3
        value=sumextedendm22(1,4-j);

        sumvalue(1,j)=(vec22(1,j))*(1/value);
    end
    extendedm22{1,i}=sumvalue;
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)


degreeofpossibility22=zeros(a*(a-1),3);
g = 1;
```

```
for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility22(g,[1 2]) = [i j];
            M1 = extendedm22{1,i};
            M2 = extendedm22{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility22(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility22(g,3) = 0;
            else
                degreeofpossibility22(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end

weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility22([find(degreeofpossibility22(:,1) == i)], [3]));
end
weights22=weights/sum(weights);

%%
%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Quality','B2:M13');

% Create output variable
relationship23 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};
fuzzyrelationshipcell23={};
[a b]=size(relationship23);
for i=1:a
    for j=i+1:a
      relationship23(j,i) = 1 / relationship23(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria2=relationship23(i,j);
        if criteria2>=1
```

```
            fuzzyrelationshipcell23{i,j}=FuzzyTFN{criteria2, 1};
        else
            fuzzyrelationshipcell23{i,j}=FuzzyTFN{round(criteria2^-1),2};
        end
    end
end

for i=1:a
    vec23=[fuzzyrelationshipcell23{i,:}];
    extendedm23{1,i}=sum(reshape(vec23,3,[]),2);
end

vec23=[extendedm23{1,:}];
sumextedendm23=sum(reshape(vec23,3,[]),2)';

for i=1:a
    vec23=[extendedm23{1,i}]';
    for j=1:3
        value=sumextedendm23(1,4-j);

        sumvalue(1,j)=(vec23(1,j))*(1/value);
    end
    extendedm23{1,i}=sumvalue;
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)


degreeofpossibility23=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility23(g,[1 2]) = [i j];
            M1 = extendedm23{1,i};
            M2 = extendedm23{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility23(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility23(g,3) = 0;
            else
                degreeofpossibility23(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
```

```
end

weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility23([find(degreeofpossibility23(:,1) == i)], [3]));
end
weights23=weights/sum(weights);

%%
%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Safety','B2:M13');

% Create output variable
relationship24 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};
fuzzyrelationshipcell24={};
[a b]=size(relationship24);
for i=1:a
    for j=i+1:a
      relationship24(j,i) = 1 / relationship24(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria4=relationship24(i,j);
        if criteria4>=1
            fuzzyrelationshipcell24{i,j}=FuzzyTFN{criteria4, 1};
        else
            fuzzyrelationshipcell24{i,j}=FuzzyTFN{round(criteria4^-1),2};
        end
    end
end

for i=1:a
    vec24=[fuzzyrelationshipcell24{i,:}];
    extendedm24{1,i}=sum(reshape(vec24,3,[]),2);
end

vec24=[extendedm24{1,:}];
sumextedendm24=sum(reshape(vec24,3,[]),2)';

for i=1:a
```

```
    vec24=[extendedm24{1,i}]';
    for j=1:3
        value=sumextedendm24(1,4-j);

        sumvalue(1,j)=(vec24(1,j))*(1/value);
    end
    extendedm24{1,i}=sumvalue;
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)


degreeofpossibility24=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility24(g,[1 2]) = [i j];
            M1 = extendedm24{1,i};
            M2 = extendedm24{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility24(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility24(g,3) = 0;
            else
                degreeofpossibility24(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end

weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility24([find(degreeofpossibility24(:,1) == i)], [3]));
end
weights24=weights/sum(weights);

%%
%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Flexibility','B2:M13');

% Create output variable
relationship25 = reshape([raw{:}],size(raw));

%Clear temporary variables
```

```
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
   [1 2 3] [1/3 1/2 1]
   [2 3 4] [1/4 1/3 1/2]
   [3 4 5] [1/5 1/4 1/3]
   [4 5 6] [1/6 1/5 1/4]
   [5 6 7] [1/7 1/6 1/5]
   [6 7 8] [1/8 1/7 1/6]
   [7 8 9] [1/9 1/8 1/7]
   [8 9 9] [1/9 1/9 1/8]};
fuzzyrelationshipcell25={};
[a b]=size(relationship25);
for i=1:a
   for j=i+1:a
     relationship25(j,i) = 1 / relationship25(i,j);
   end
end

for i=1:a
   for j=1:b
      criteria5=relationship25(i,j);
      if criteria5>=1
         fuzzyrelationshipcell25{i,j}=FuzzyTFN{criteria5, 1};
      else
         fuzzyrelationshipcell25{i,j}=FuzzyTFN{round(criteria5^-1),2};
      end
   end
end

for i=1:a
   vec25=[fuzzyrelationshipcell25{i,:}];
   extendedm25{1,i}=sum(reshape(vec25,3,[]),2);
end

vec25=[extendedm25{1,:}];
sumextedendm25=sum(reshape(vec25,3,[]),2)';

for i=1:a
   vec25=[extendedm25{1,i}]';
   for j=1:3
      value=sumextedendm25(1,4-j);

      sumvalue(1,j)=(vec25(1,j))*(1/value);
   end
   extendedm25{1,i}=sumvalue;
end

% degree of possibility calculation
%            /---
%            | 1    if m2>=m1
%            |
%            | 0    if l1>=l2
% V(M2>=M1) = <
%            |     l1-u2
```

```
%             | --------------- otherwise
%             | (m1-u2)-(m1-l1)


degreeofpossibility25=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility25(g,[1 2]) = [i j];
            M1 = extendedm25{1,i};
            M2 = extendedm25{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility25(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility25(g,3) = 0;
            else
                degreeofpossibility25(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end

weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility25([find(degreeofpossibility25(:,1) == i)], [3]));
end
weights25=weights/sum(weights);

W2=[weights21;weights22;weights23;weights24;weights25]


%%
%% Calculating W3
% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','W31','B2:F6');

% Create output variable
relationship31 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};
fuzzyrelationshipcell31={};
```

```
[a b]=size(relationship31);
for i=1:a
   for j=i+1:a
     relationship31(j,i) = 1 / relationship31(i,j);
   end
end

for i=1:a
   for j=1:b
      criteria31=relationship31(i,j);
      if criteria31>=1
         fuzzyrelationshipcell31{i,j}=FuzzyTFN{criteria31, 1};
      else
         fuzzyrelationshipcell31{i,j}=FuzzyTFN{round(criteria31^-1),2};
      end
   end
end

for i=1:a
   vec31=[fuzzyrelationshipcell31{i,:}];
   extendedm31{1,i}=sum(reshape(vec31,3,[]),2);
end

vec31=[extendedm31{1,:}];
sumextedendm31=sum(reshape(vec31,3,[]),2)';

for i=1:a
   vec31=[extendedm31{1,i}]';
   for j=1:3
      value=sumextedendm31(1,4-j);

      sumvalue(1,j)=(vec31(1,j))*(1/value);
   end
   extendedm31{1,i}=sumvalue;
end

% degree of possibility calculation
%            /---
%            | 1    if m2>=m1
%            |
%            | 0    if l1>=l2
% V(M2>=M1) = <
%            |     l1-u2
%            | --------------- otherwise
%            | (m1-u2)-(m1-l1)


degreeofpossibility31=zeros(a*(a-1),3);
g = 1;

for i=1:a
   for j=1:a
      if i~=j
         degreeofpossibility31(g,[1 2]) = [i j];
         M1 = extendedm31{1,i};
```

```
            M2 = extendedm31{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility31(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility31(g,3) = 0;
            else
                degreeofpossibility31(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end

weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility31([find(degreeofpossibility31(:,1) == i)], [3]));
end
weights31=weights/sum(weights);
%%
%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','W32','B2:F6');

% Create output variable
relationship32 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell32={};
[a b]=size(relationship32);
for i=1:a
    for j=i+1:a
      relationship32(j,i) = 1 / relationship32(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria32=relationship32(i,j);
        if criteria32>=1
            fuzzyrelationshipcell32{i,j}=FuzzyTFN{criteria32, 1};
        else
            fuzzyrelationshipcell32{i,j}=FuzzyTFN{round(criteria32^-1),2};
        end
    end
```

```
end

for i=1:a
    vec32=[fuzzyrelationshipcell32{i,:}];
    extendedm32{1,i}=sum(reshape(vec32,3,[]),2);
end

vec32=[extendedm32{1,:}];
sumextedendm32=sum(reshape(vec32,3,[]),2)';

for i=1:a
    vec32=[extendedm32{1,i}]';
    for j=1:3
        value=sumextedendm32(1,4-j);

        sumvalue(1,j)=(vec32(1,j))*(1/value);
    end
    extendedm32{1,i}=sumvalue;
end

% degree of possibility calculation
%              /---
%              | 1    if m2>=m1
%              |
%              | 0    if l1>=l2
% V(M2>=M1) = <
%              |     l1-u2
%              | --------------- otherwise
%              | (m1-u2)-(m1-l1)


degreeofpossibility32=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility32(g,[1 2]) = [i j];
            M1 = extendedm32{1,i};
            M2 = extendedm32{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility32(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility32(g,3) = 0;
            else
                degreeofpossibility32(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end

weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility32([find(degreeofpossibility32(:,1) == i)], [3]));
```

```
end
weights32=weights/sum(weights);
%%
%%
%Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','W33','B2:F6');

% Create output variable
relationship33 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell33={};
[a b]=size(relationship33);
for i=1:a
    for j=i+1:a
      relationship33(j,i) = 1 / relationship33(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria33=relationship33(i,j);
        if criteria33>=1
            fuzzyrelationshipcell33{i,j}=FuzzyTFN{criteria33, 1};
        else
            fuzzyrelationshipcell33{i,j}=FuzzyTFN{round(criteria33^-1),2};
        end
    end
end

for i=1:a
    vec33=[fuzzyrelationshipcell33{i,:}];
    extendedm33{1,i}=sum(reshape(vec33,3,[]),2);
end

vec33=[extendedm33{1,:}];
sumextedendm33=sum(reshape(vec33,3,[]),2)';

for i=1:a
    vec33=[extendedm33{1,i}]';
    for j=1:3
        value=sumextedendm33(1,4-j);
```

```
        sumvalue(1,j)=(vec33(1,j))*(1/value);
    end
    extendedm33{1,i}=sumvalue;
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)


degreeofpossibility33=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility33(g,[1 2]) = [i j];
            M1 = extendedm33{1,i};
            M2 = extendedm33{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility33(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility33(g,3) = 0;
            else
                degreeofpossibility33(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end

weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility33([find(degreeofpossibility33(:,1) == i)], [3]));
end
weights33=weights/sum(weights);

%%
%%
%Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','W34','B2:F6');

% Create output variable
relationship34 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
```

```
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell34={};
[a b]=size(relationship34);
for i=1:a
    for j=i+1:a
      relationship34(j,i) = 1 / relationship34(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria34=relationship34(i,j);
        if criteria34>=1
            fuzzyrelationshipcell34{i,j}=FuzzyTFN{criteria34, 1};
        else
            fuzzyrelationshipcell34{i,j}=FuzzyTFN{round(criteria34^-1),2};
        end
    end
end

for i=1:a
    vec34=[fuzzyrelationshipcell34{i,:}];
    extendedm34{1,i}=sum(reshape(vec34,3,[]),2);
end

vec34=[extendedm34{1,:}];
sumextedendm34=sum(reshape(vec34,3,[]),2)';

for i=1:a
    vec34=[extendedm34{1,i}]';
    for j=1:3
        value=sumextedendm34(1,4-j);

        sumvalue(1,j)=(vec34(1,j))*(1/value);
    end
    extendedm34{1,i}=sumvalue;
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)
```

```
degreeofpossibility34=zeros(a*(a-1),3);
g = 1;

for i=1:a
   for j=1:a
      if i~=j
         degreeofpossibility34(g,[1 2]) = [i j];
         M1 = extendedm34{1,i};
         M2 = extendedm34{1,j};
         if M1(1,2) >= M2(1,2)
            degreeofpossibility34(g,3) = 1;
         elseif M2(1,1) >= M1(1,3)
            degreeofpossibility34(g,3) = 0;
         else
            degreeofpossibility34(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
         end
         g=g+1;
      end
   end
end

weights = zeros(1,a);
for i=1:a,
   weights(1,i) = min(degreeofpossibility34([find(degreeofpossibility34(:,1) == i)], [3]));
end
weights34=weights/sum(weights);
%%
% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','W35','B2:F6');

% Create output variable
relationship35 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
   [1 2 3] [1/3 1/2 1]
   [2 3 4] [1/4 1/3 1/2]
   [3 4 5] [1/5 1/4 1/3]
   [4 5 6] [1/6 1/5 1/4]
   [5 6 7] [1/7 1/6 1/5]
   [6 7 8] [1/8 1/7 1/6]
   [7 8 9] [1/9 1/8 1/7]
   [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell35={};
[a b]=size(relationship35);
for i=1:a
   for j=i+1:a
     relationship35(j,i) = 1 / relationship35(i,j);
   end
end
```

```
for i=1:a
   for j=1:b
      criteria35=relationship35(i,j);
      if criteria35>=1
         fuzzyrelationshipcell35{i,j}=FuzzyTFN{criteria35, 1};
      else
         fuzzyrelationshipcell35{i,j}=FuzzyTFN{round(criteria35^-1),2};
      end
   end
end

for i=1:a
   vec35=[fuzzyrelationshipcell35{i,:}];
   extendedm35{1,i}=sum(reshape(vec35,3,[]),2);
end

vec35=[extendedm35{1,:}];
sumextedendm35=sum(reshape(vec35,3,[]),2)';

for i=1:a
   vec35=[extendedm35{1,i}]';
   for j=1:3
      value=sumextedendm35(1,4-j);

      sumvalue(1,j)=(vec35(1,j))*(1/value);
   end
   extendedm35{1,i}=sumvalue;
end

% degree of possibility calculation
%            /---
%            | 1    if m2>=m1
%            |
%            | 0    if l1>=l2
% V(M2>=M1) = <
%            |     l1-u2
%            | --------------- otherwise
%            | (m1-u2)-(m1-l1)


degreeofpossibility35=zeros(a*(a-1),3);
g = 1;

for i=1:a
   for j=1:a
      if i~=j
         degreeofpossibility35(g,[1 2]) = [i j];
         M1 = extendedm35{1,i};
         M2 = extendedm35{1,j};
         if M1(1,2) >= M2(1,2)
            degreeofpossibility35(g,3) = 1;
         elseif M2(1,1) >= M1(1,3)
            degreeofpossibility35(g,3) = 0;
         else
```

```
            degreeofpossibility35(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
        end
        g=g+1;
      end
   end
end

weights = zeros(1,a);
for i=1:a,
   weights(1,i) = min(degreeofpossibility35([find(degreeofpossibility35(:,1) == i)], [3]));
end
weights35=weights/sum(weights);

W3=[weights31;weights32;weights33;weights34;weights35]

%%
%% Claculating weight4
%%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Cost per part','B2:M13');

%Create output variable
relationship41 = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
   [1 2 3] [1/3 1/2 1]
   [2 3 4] [1/4 1/3 1/2]
   [3 4 5] [1/5 1/4 1/3]
   [4 5 6] [1/6 1/5 1/4]
   [5 6 7] [1/7 1/6 1/5]
   [6 7 8] [1/8 1/7 1/6]
   [7 8 9] [1/9 1/8 1/7]
   [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell41={};
[a b]=size(relationship41);
for i=1:a
   for j=i+1:a
      relationship41(j,i) = 1 / relationship41(i,j);
   end
end

for i=1:a
   for j=1:b
      criteria41=relationship41(i,j);
      if criteria41>=1
         fuzzyrelationshipcell41{i,j}=FuzzyTFN{criteria41, 1};
      else
         fuzzyrelationshipcell41{i,j}=FuzzyTFN{round(criteria41^-1),2};
      end
   end
end
```

```
for i=1:a
    vec41=[fuzzyrelationshipcell41{i,:}];
    extendedm41{1,i}=sum(reshape(vec41,3,[]),2);
end

vec41=[extendedm41{1,:}];
sumextedendm41=sum(reshape(vec41,3,[]),2)';

for i=1:a
    vec41=[extendedm41{1,i}]';
    for j=1:3
        value=sumextedendm41(1,4-j);

        sumvalue(1,j)=(vec41(1,j))*(1/value);
    end
    extendedm41{1,i}=sumvalue;
end

% degree of possibility calculation
%             /---
%             | 1    if m2>=m1
%             |
%             | 0    if l1>=l2
% V(M2>=M1) = <
%             |     l1-u2
%             | --------------- otherwise
%             | (m1-u2)-(m1-l1)


degreeofpossibility41=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility41(g,[1 2]) = [i j];
            M1 = extendedm41{1,i};
            M2 = extendedm41{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility41(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility41(g,3) = 0;
            else
                degreeofpossibility41(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility41([find(degreeofpossibility41(:,1) == i)], [3]));
end
weights41=weights/sum(weights);
%%
```

```
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Total inventory cost','B2:M13');

%Create output variable
relationship42= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell42={};
[a b]=size(relationship42);
for i=1:a
    for j=i+1:a
      relationship42(j,i) = 1 / relationship42(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria42=relationship42(i,j);
        if criteria42>=1
            fuzzyrelationshipcell42{i,j}=FuzzyTFN{criteria42, 1};
        else
            fuzzyrelationshipcell42{i,j}=FuzzyTFN{round(criteria42^-1),2};
        end
    end
end

for i=1:a
    vec42=[fuzzyrelationshipcell42{i,:}];
    extendedm42{1,i}=sum(reshape(vec42,3,[]),2);
end

vec42=[extendedm42{1,:}];
sumextedendm42=sum(reshape(vec42,3,[]),2)';

for i=1:a
    vec42=[extendedm42{1,i}]';
    for j=1:3
        value=sumextedendm42(1,4-j);

        sumvalue(1,j)=(vec42(1,j))*(1/value);
    end
    extendedm42{1,i}=sumvalue;
```

```
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)


degreeofpossibility42=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility42(g,[1 2]) = [i j];
            M1 = extendedm42{1,i};
            M2 = extendedm42{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility42(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility42(g,3) = 0;
            else
                degreeofpossibility42(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility42([find(degreeofpossibility42(:,1) == i)], [3]));
end
weights42=weights/sum(weights);
%%
%%%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Transportation cost','B2:M13');

%Create output variable
relationship43= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
```

```
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell43={};
[a b]=size(relationship43);
for i=1:a
    for j=i+1:a
      relationship43(j,i) = 1 / relationship43(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria43=relationship43(i,j);
        if criteria43>=1
            fuzzyrelationshipcell43{i,j}=FuzzyTFN{criteria43, 1};
        else
            fuzzyrelationshipcell43{i,j}=FuzzyTFN{round(criteria43^-1),2};
        end
    end
end

for i=1:a
    vec43=[fuzzyrelationshipcell43{i,:}];
    extendedm43{1,i}=sum(reshape(vec43,3,[]),2);
end

vec43=[extendedm43{1,:}];
sumextedendm43=sum(reshape(vec43,3,[]),2)';

for i=1:a
    vec43=[extendedm43{1,i}]';
    for j=1:3
        value=sumextedendm43(1,4-j);

        sumvalue(1,j)=(vec43(1,j))*(1/value);
    end
    extendedm43{1,i}=sumvalue;
end

% degree of possibility calculation
%             /---
%             | 1    if m2>=m1
%             |
%             | 0    if l1>=l2
% V(M2>=M1) = <
%             |     l1-u2
%             | --------------- otherwise
%             | (m1-u2)-(m1-l1)


degreeofpossibility43=zeros(a*(a-1),3);
g = 1;

for i=1:a
```

```
    for j=1:a
        if i~=j
            degreeofpossibility43(g,[1 2]) = [i j];
            M1 = extendedm43{1,i};
            M2 = extendedm43{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility43(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility43(g,3) = 0;
            else
                degreeofpossibility43(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility43([find(degreeofpossibility43(:,1) == i)], [3]));
end
weights43=weights/sum(weights);
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Setup time','B2:M13');

%Create output variable
relationship44= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell44={};
[a b]=size(relationship44);
for i=1:a
    for j=i+1:a
      relationship44(j,i) = 1 / relationship44(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria44=relationship44(i,j);
        if criteria44>=1
            fuzzyrelationshipcell44{i,j}=FuzzyTFN{criteria44, 1};
        else
```

```
            fuzzyrelationshipcell44{i,j}=FuzzyTFN{round(criteria44^-1),2};
        end
    end
end

for i=1:a
    vec44=[fuzzyrelationshipcell44{i,:}];
    extendedm44{1,i}=sum(reshape(vec44,3,[]),2);
end

vec44=[extendedm44{1,:}];
sumextedendm44=sum(reshape(vec44,3,[]),2)';

for i=1:a
    vec44=[extendedm44{1,i}]';
    for j=1:3
        value=sumextedendm44(1,4-j);

        sumvalue(1,j)=(vec44(1,j))*(1/value);
    end
    extendedm44{1,i}=sumvalue;
end

% degree of possibility calculation
%             /---
%             | 1    if m2>=m1
%             |
%             | 0    if l1>=l2
% V(M2>=M1) = <
%             |     l1-u2
%             | --------------- otherwise
%             | (m1-u2)-(m1-l1)


degreeofpossibility44=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility44(g,[1 2]) = [i j];
            M1 = extendedm44{1,i};
            M2 = extendedm44{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility44(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility44(g,3) = 0;
            else
                degreeofpossibility44(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
```

```
for i=1:a,
    weights(1,i) = min(degreeofpossibility44([find(degreeofpossibility44(:,1) == i)], [3]));
end
weights44=weights/sum(weights);
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Manufacturing lead time','B2:M13');

%Create output variable
relationship45= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell45={};
[a b]=size(relationship45);
for i=1:a
    for j=i+1:a
      relationship45(j,i) = 1 / relationship45(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria45=relationship45(i,j);
        if criteria45>=1
            fuzzyrelationshipcell45{i,j}=FuzzyTFN{criteria45, 1};
        else
            fuzzyrelationshipcell45{i,j}=FuzzyTFN{round(criteria45^-1),2};
        end
    end
end

for i=1:a
    vec45=[fuzzyrelationshipcell45{i,:}];
    extendedm45{1,i}=sum(reshape(vec45,3,[]),2);
end

vec45=[extendedm45{1,:}];
sumextedendm45=sum(reshape(vec45,3,[]),2)';

for i=1:a
    vec45=[extendedm45{1,i}]';
    for j=1:3
```

```
        value=sumextedendm45(1,4-j);

        sumvalue(1,j)=(vec45(1,j))*(1/value);
    end
    extendedm45{1,i}=sumvalue;
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)


degreeofpossibility45=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility45(g,[1 2]) = [i j];
            M1 = extendedm45{1,i};
            M2 = extendedm45{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility45(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility45(g,3) = 0;
            else
                degreeofpossibility45(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility45([find(degreeofpossibility45(:,1) == i)], [3]));
end
weights45=weights/sum(weights);
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Labour productivity','B2:M13');

%Create output variable
relationship46= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
```

```
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell46={};
[a b]=size(relationship46);
for i=1:a
    for j=i+1:a
      relationship46(j,i) = 1 / relationship46(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria46=relationship46(i,j);
        if criteria46>=1
            fuzzyrelationshipcell46{i,j}=FuzzyTFN{criteria46, 1};
        else
            fuzzyrelationshipcell46{i,j}=FuzzyTFN{round(criteria46^-1),2};
        end
    end
end

for i=1:a
    vec46=[fuzzyrelationshipcell46{i,:}];
    extendedm46{1,i}=sum(reshape(vec46,3,[]),2);
end

vec46=[extendedm46{1,:}];
sumextedendm46=sum(reshape(vec46,3,[]),2)';

for i=1:a
    vec46=[extendedm46{1,i}]';
    for j=1:3
        value=sumextedendm46(1,4-j);

        sumvalue(1,j)=(vec46(1,j))*(1/value);
    end
    extendedm46{1,i}=sumvalue;
end

% degree of possibility calculation
%            /---
%            | 1    if m2>=m1
%            |
%            | 0    if l1>=l2
% V(M2>=M1) = <
%            |     l1-u2
%            | --------------- otherwise
%            | (m1-u2)-(m1-l1)
```

```
degreeofpossibility46=zeros(a*(a-1),3);
g = 1;

for i=1:a
   for j=1:a
      if i~=j
         degreeofpossibility46(g,[1 2]) = [i j];
         M1 = extendedm46{1,i};
         M2 = extendedm46{1,j};
         if M1(1,2) >= M2(1,2)
            degreeofpossibility46(g,3) = 1;
         elseif M2(1,1) >= M1(1,3)
            degreeofpossibility46(g,3) = 0;
         else
            degreeofpossibility46(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
         end
         g=g+1;
      end
   end
end
weights = zeros(1,a);
for i=1:a,
   weights(1,i) = min(degreeofpossibility46([find(degreeofpossibility46(:,1) == i)], [3]));
end
weights46=weights/sum(weights);
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','OEE','B2:M13');

%Create output variable
relationship47= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
   [1 2 3] [1/3 1/2 1]
   [2 3 4] [1/4 1/3 1/2]
   [3 4 5] [1/5 1/4 1/3]
   [4 5 6] [1/6 1/5 1/4]
   [5 6 7] [1/7 1/6 1/5]
   [6 7 8] [1/8 1/7 1/6]
   [7 8 9] [1/9 1/8 1/7]
   [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell47={};
[a b]=size(relationship47);
for i=1:a
   for j=i+1:a
     relationship47(j,i) = 1 / relationship47(i,j);
   end
end

for i=1:a
```

```
    for j=1:b
        criteria47=relationship47(i,j);
        if criteria47>=1
            fuzzyrelationshipcell47{i,j}=FuzzyTFN{criteria47, 1};
        else
            fuzzyrelationshipcell47{i,j}=FuzzyTFN{round(criteria47^-1),2};
        end
    end
end

for i=1:a
    vec47=[fuzzyrelationshipcell47{i,:}];
    extendedm47{1,i}=sum(reshape(vec47,3,[]),2);
end

vec47=[extendedm47{1,:}];
sumextedendm47=sum(reshape(vec47,3,[]),2)';

for i=1:a
    vec47=[extendedm47{1,i}]';
    for j=1:3
        value=sumextedendm47(1,4-j);

        sumvalue(1,j)=(vec47(1,j))*(1/value);
    end
    extendedm47{1,i}=sumvalue;
end

% degree of possibility calculation
%             /---
%             | 1    if m2>=m1
%             |
%             | 0    if l1>=l2
% V(M2>=M1) = <
%             |     l1-u2
%             | --------------- otherwise
%             | (m1-u2)-(m1-l1)


degreeofpossibility47=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility47(g,[1 2]) = [i j];
            M1 = extendedm47{1,i};
            M2 = extendedm47{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility47(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility47(g,3) = 0;
            else
                degreeofpossibility47(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
```

```
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility47([find(degreeofpossibility47(:,1) == i)], [3]));
end
weights47=weights/sum(weights);
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Rework rate','B2:M13');

%Create output variable
relationship48= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell48={};
[a b]=size(relationship48);
for i=1:a
    for j=i+1:a
      relationship48(j,i) = 1 / relationship48(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria48=relationship48(i,j);
        if criteria48>=1
            fuzzyrelationshipcell48{i,j}=FuzzyTFN{criteria48, 1};
        else
            fuzzyrelationshipcell48{i,j}=FuzzyTFN{round(criteria48^-1),2};
        end
    end
end

for i=1:a
    vec48=[fuzzyrelationshipcell48{i,:}];
    extendedm48{1,i}=sum(reshape(vec48,3,[]),2);
end

vec48=[extendedm48{1,:}];
sumextedendm48=sum(reshape(vec48,3,[]),2)';
```

```
for i=1:a
    vec48=[extendedm48{1,i}]';
    for j=1:3
        value=sumextedendm48(1,4-j);

        sumvalue(1,j)=(vec48(1,j))*(1/value);
    end
    extendedm48{1,i}=sumvalue;
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)


degreeofpossibility48=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility48(g,[1 2]) = [i j];
            M1 = extendedm48{1,i};
            M2 = extendedm48{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility48(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility48(g,3) = 0;
            else
                degreeofpossibility48(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility48([find(degreeofpossibility48(:,1) == i)], [3]));
end
weights48=weights/sum(weights);
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Customer satisfaction','B2:M13');

%Create output variable
relationship49= reshape([raw{:}],size(raw));
```

```
% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
   [1 2 3] [1/3 1/2 1]
   [2 3 4] [1/4 1/3 1/2]
   [3 4 5] [1/5 1/4 1/3]
   [4 5 6] [1/6 1/5 1/4]
   [5 6 7] [1/7 1/6 1/5]
   [6 7 8] [1/8 1/7 1/6]
   [7 8 9] [1/9 1/8 1/7]
   [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell49={};
[a b]=size(relationship49);
for i=1:a
   for j=i+1:a
     relationship49(j,i) = 1 / relationship49(i,j);
   end
end

for i=1:a
   for j=1:b
      criteria49=relationship49(i,j);
      if criteria49>=1
         fuzzyrelationshipcell49{i,j}=FuzzyTFN{criteria49, 1};
      else
         fuzzyrelationshipcell49{i,j}=FuzzyTFN{round(criteria49^-1),2};
      end
   end
end

for i=1:a
   vec49=[fuzzyrelationshipcell49{i,:}];
   extendedm49{1,i}=sum(reshape(vec49,3,[]),2);
end

vec49=[extendedm49{1,:}];
sumextedendm49=sum(reshape(vec49,3,[]),2)';

for i=1:a
   vec49=[extendedm49{1,i}]';
   for j=1:3
      value=sumextedendm49(1,4-j);

      sumvalue(1,j)=(vec49(1,j))*(1/value);
   end
   extendedm49{1,i}=sumvalue;
end

% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
```

```
% V(M2>=M1) = <
%             |     l1-u2
%             | --------------- otherwise
%             | (m1-u2)-(m1-l1)


degreeofpossibility49=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility49(g,[1 2]) = [i j];
            M1 = extendedm49{1,i};
            M2 = extendedm49{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility49(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility49(g,3) = 0;
            else
                degreeofpossibility49(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility49([find(degreeofpossibility49(:,1) == i)], [3]));
end
weights49=weights/sum(weights);
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','No of work-related injuries','B2:M13');

%Create output variable
relationship410= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell410={};
[a b]=size(relationship410);
for i=1:a
```

```
    for j=i+1:a
      relationship410(j,i) = 1 / relationship410(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria410=relationship410(i,j);
        if criteria410>=1
            fuzzyrelationshipcell410{i,j}=FuzzyTFN{criteria410, 1};
        else
            fuzzyrelationshipcell410{i,j}=FuzzyTFN{round(criteria410^-1),2};
        end
    end
end

for i=1:a
    vec410=[fuzzyrelationshipcell410{i,:}];
    extendedm410{1,i}=sum(reshape(vec410,3,[]),2);
end

vec410=[extendedm410{1,:}];
sumextedendm410=sum(reshape(vec410,3,[]),2)';

for i=1:a
    vec410=[extendedm410{1,i}]';
    for j=1:3
        value=sumextedendm410(1,4-j);

        sumvalue(1,j)=(vec410(1,j))*(1/value);
    end
    extendedm410{1,i}=sumvalue;
end

% degree of possibility calculation
%             /---
%             | 1    if m2>=m1
%             |
%             | 0    if l1>=l2
% V(M2>=M1) = <
%             |     l1-u2
%             | --------------- otherwise
%             | (m1-u2)-(m1-l1)


degreeofpossibility410=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility410(g,[1 2]) = [i j];
            M1 = extendedm410{1,i};
            M2 = extendedm410{1,j};
            if M1(1,2) >= M2(1,2)
```

```
                degreeofpossibility410(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility410(g,3) = 0;
            else
                degreeofpossibility410(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility410([find(degreeofpossibility410(:,1) == i)], [3]));
end
weights410=weights/sum(weights);
%%
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Supplier responsiveness','B2:M13');

%Create output variable
relationship411= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
    [1 2 3] [1/3 1/2 1]
    [2 3 4] [1/4 1/3 1/2]
    [3 4 5] [1/5 1/4 1/3]
    [4 5 6] [1/6 1/5 1/4]
    [5 6 7] [1/7 1/6 1/5]
    [6 7 8] [1/8 1/7 1/6]
    [7 8 9] [1/9 1/8 1/7]
    [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell411={};
[a b]=size(relationship411);
for i=1:a
    for j=i+1:a
      relationship411(j,i) = 1 / relationship411(i,j);
    end
end

for i=1:a
    for j=1:b
        criteria411=relationship411(i,j);
        if criteria411>=1
            fuzzyrelationshipcell411{i,j}=FuzzyTFN{criteria411, 1};
        else
            fuzzyrelationshipcell411{i,j}=FuzzyTFN{round(criteria411^-1),2};
        end
    end
end
```

```
for i=1:a
   vec411=[fuzzyrelationshipcell411{i,:}];
   extendedm411{1,i}=sum(reshape(vec411,3,[]),2);
end

vec411=[extendedm411{1,:}];
sumextedendm411=sum(reshape(vec411,3,[]),2)';

for i=1:a
   vec411=[extendedm411{1,i}]';
   for j=1:3
      value=sumextedendm411(1,4-j);

      sumvalue(1,j)=(vec411(1,j))*(1/value);
   end
   extendedm411{1,i}=sumvalue;
end

% degree of possibility calculation
%              /---
%              | 1    if m2>=m1
%              |
%              | 0    if l1>=l2
% V(M2>=M1) = <
%              |     l1-u2
%              | --------------- otherwise
%              | (m1-u2)-(m1-l1)


degreeofpossibility411=zeros(a*(a-1),3);
g = 1;

for i=1:a
   for j=1:a
      if i~=j
         degreeofpossibility411(g,[1 2]) = [i j];
         M1 = extendedm411{1,i};
         M2 = extendedm411{1,j};
         if M1(1,2) >= M2(1,2)
            degreeofpossibility411(g,3) = 1;
         elseif M2(1,1) >= M1(1,3)
            degreeofpossibility411(g,3) = 0;
         else
            degreeofpossibility411(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
         end
         g=g+1;
      end
   end
end
weights = zeros(1,a);
for i=1:a,
   weights(1,i) = min(degreeofpossibility411([find(degreeofpossibility411(:,1) == i)], [3]));
end
weights411=weights/sum(weights);
%%
```

```
%%%% Import the data
[~, ~, raw] = xlsread('F:\PhD project\Preliminary results\Chapter 5\relationship.xlsx','Ontime delivery','B2:M13');

%Create output variable
relationship412= reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

FuzzyTFN={[1 1 1] [1 1 1]
   [1 2 3] [1/3 1/2 1]
   [2 3 4] [1/4 1/3 1/2]
   [3 4 5] [1/5 1/4 1/3]
   [4 5 6] [1/6 1/5 1/4]
   [5 6 7] [1/7 1/6 1/5]
   [6 7 8] [1/8 1/7 1/6]
   [7 8 9] [1/9 1/8 1/7]
   [8 9 9] [1/9 1/9 1/8]};

fuzzyrelationshipcell412={};
[a b]=size(relationship412);
for i=1:a
   for j=i+1:a
     relationship412(j,i) = 1 / relationship412(i,j);
   end
end

for i=1:a
   for j=1:b
      criteria412=relationship412(i,j);
      if criteria412>=1
         fuzzyrelationshipcell412{i,j}=FuzzyTFN{criteria412, 1};
      else
         fuzzyrelationshipcell412{i,j}=FuzzyTFN{round(criteria412^-1),2};
      end
   end
end

for i=1:a
   vec412=[fuzzyrelationshipcell412{i,:}];
   extendedm412{1,i}=sum(reshape(vec412,3,[]),2);
end

vec412=[extendedm412{1,:}];
sumextedendm412=sum(reshape(vec412,3,[]),2)';

for i=1:a
   vec412=[extendedm412{1,i}]';
   for j=1:3
      value=sumextedendm412(1,4-j);

      sumvalue(1,j)=(vec412(1,j))*(1/value);
   end
   extendedm412{1,i}=sumvalue;
end
```

```
% degree of possibility calculation
%           /---
%           | 1    if m2>=m1
%           |
%           | 0    if l1>=l2
% V(M2>=M1) = <
%           |     l1-u2
%           | --------------- otherwise
%           | (m1-u2)-(m1-l1)


degreeofpossibility412=zeros(a*(a-1),3);
g = 1;

for i=1:a
    for j=1:a
        if i~=j
            degreeofpossibility412(g,[1 2]) = [i j];
            M1 = extendedm412{1,i}I;
            M2 = extendedm412{1,j};
            if M1(1,2) >= M2(1,2)
                degreeofpossibility412(g,3) = 1;
            elseif M2(1,1) >= M1(1,3)
                degreeofpossibility412(g,3) = 0;
            else
                degreeofpossibility412(g,3) = (M2(1,1)-M1(1,3))/((M1(1,2)-M1(1,3))-(M2(1,2)-M2(1,1)));
            end
            g=g+1;
        end
    end
end
weights = zeros(1,a);
for i=1:a,
    weights(1,i) = min(degreeofpossibility412([find(degreeofpossibility412(:,1) == i)], [3]));
end
weights412=weights/sum(weights);
%%
W4=[weights41;weights42;weights43;weights44;weights45;weights46;weights47;weights48;weights49;weights410;
weights411;weights412]


%%
measureweights=W3'*(W1');
metricsweights=W4'*(W2');
ANPweights=metricsweights*measureweights
```

MATLAB code for measuring the overall leanness level

```
% fuzzy-based leanness assessment model bye using equal interrelationships
% In this model these performance metrics were used:
% Financial:Manufacturing cost, Total inventory cost,Transportation cost
% Produtivity: Time to assemble, Labour productivity, Overall equipment efficiency
% Quality: Rework rate,Custmer satisfaction
% Health and safety: Operator satisfaction
% Flexibility: Supplier responsiveness, On-time delivery

c=4; y=[0 1 0];% the membership value of fuzzy number for their plots
B=zeros(12,9);
STD=zeros(12,1);
diff=zeros(12,9);
Simil=zeros(12,9);
TFN=zeros(12,3); %Triangular fuzzy number
i=12;

NAME={'Cost per part';'Total inventory cost';'Transportation cost';'Seutup time';'Manufacturing lead time';'Labour productivity';
   'Overall Equipment Efficiency';'Rework rate';'Custmer satisfaction';'Number of work-related injuries';'Supplier responsiveness';
   'On-time delivery'};
A= xlsread('E:\PhD project\Preliminary results\Chapter 5\performance metrics values.xlsx','1','C3:L14');

A=sort(A,2);

% calculating the adjacent data
for i=1:12
   for j=1:9
      B(i,j)=A(i,j+1)-A(i,j);
   end
end

% Standard deviation of each performance metrics
for i=1:12
   STD(i,1)=std(B(i,:),1);
end


% Ratio of Difference to Standard Deviation Values
% c=4
for i=1:12
   for j=1:9
      diff(i,j)=B(i,j)/(4*STD(i,1));
   end
end

% Similarity Value of each performance metrics
for i=1:12
   for j=1:9
      if diff(i,j)<1
         Simil(i,j)=1-diff(i,j);
      else
```

```
            Simil(i,j)=0;
        end
    end
end

% for i=1:12
%     for j=1:9
%         Simil(i,j)=1-diff(i,j);
%         if Simil(i,j)<0
%             Simil(i,j)=0;
%         end
%     end
% end
%
% % calculating central vertex point
for i=1:12


TFN(i,2)=((A(i,1)*Simil(i,1))+A(i,2)*(Simil(i,1)+Simil(i,2))/2+A(i,3)*(Simil(i,2)+Simil(i,3))/2+A(i,4)*(Simil(i,3)+
Simil(i,4))/2+A(i,5)*(Simil(i,4)+Simil(i,5))/2+A(i,6)*(Simil(i,5)+Simil(i,6))/2+A(i,7)*(Simil(i,6)+Simil(i,7))/2+(A(
i,8)*Simil(i,7)))/(Simil(i,1)+(Simil(i,1)+Simil(i,2))/2+(Simil(i,2)+Simil(i,3))/2+(Simil(i,3)+Simil(i,4))/2+(Simil(i,4)
+Simil(i,5))/2+(Simil(i,5)+Simil(i,6))/2+(Simil(i,6)+Simil(i,7))/2+Simil(i,7));

    Min=min(Simil(i,:));
    TFN(i,1)=TFN(i,2)-(TFN(i,2)-A(i,1))/(1-Min);
    TFN(i,3)=TFN(i,2)+(A(i,8)-TFN(i,2))/(1-Min);

end
format bank
TFN;
% ploting fuzzy numbers
for i=1:12
    subplot(4,3,i)
    plot(TFN(i,:),y)
    xlabel(NAME{i})
    ylabel('Membership value')
end

figure
for i=[1,2,3,4,8,10]
        subplot(4,3,i)
        x=TFN(i,1):0.001:TFN(i,3);
        z=(TFN(i,3)-x)/(TFN(i,3)-TFN(i,1));
        plot(x,z)
        xlabel(NAME{i})
        ylabel('Uniformity_Function')
        for i=[5,6,7,9,11,12]
            subplot(4,3,i)
            x=TFN(i,1):0.001:TFN(i,3);
            u=(x-TFN(i,1))/(TFN(i,3)-TFN(i,1));
            plot(x,u)
            xlabel(NAME{i})
            ylabel('Uniformity_Function')
        end
end
```

```
% computing the current leanness level and optimum value
leanness_level=zeros(12,4);
current_value=xlsread('E:\PhD project\Preliminary results\Chapter 5\performance metrics values.xlsx','1','N3:N14');
for i=1:4
   leanness_level(i,1)=current_value(i);
   leanness_level(i,2)=(TFN(i,3)-current_value(i))/(TFN(i,3)-TFN(i,1));
   leanness_level(i,3)=TFN(i,2);
   leanness_level(i,4)=(TFN(i,3)-TFN(i,2))/(TFN(i,3)-TFN(i,1));
end
for i=8
   leanness_level(i,1)=current_value(i);
   leanness_level(i,2)=(TFN(i,3)-current_value(i))/(TFN(i,3)-TFN(i,1));
   leanness_level(i,3)=TFN(i,2);
   leanness_level(i,4)=(TFN(i,3)-TFN(i,2))/(TFN(i,3)-TFN(i,1));
end
for i=10
   leanness_level(i,1)=current_value(i);
   leanness_level(i,2)=(TFN(i,3)-current_value(i))/(TFN(i,3)-TFN(i,1));
   leanness_level(i,3)=TFN(i,2);
   leanness_level(i,4)=(TFN(i,3)-TFN(i,2))/(TFN(i,3)-TFN(i,1));
end
for i=5:7
   leanness_level(i,1)=current_value(i);
   leanness_level(i,2)=(current_value(i)-TFN(i,3))/(TFN(i,3)-TFN(i,1));
   leanness_level(i,3)=TFN(i,2);
   leanness_level(i,4)=(TFN(i,3)-TFN(i,2))/(TFN(i,3)-TFN(i,1));
end
for i=9
   leanness_level(i,1)=current_value(i);
   leanness_level(i,2)=(current_value(i)-TFN(i,3))/(TFN(i,3)-TFN(i,1));
   leanness_level(i,3)=TFN(i,2);
   leanness_level(i,4)=(TFN(i,3)-TFN(i,2))/(TFN(i,3)-TFN(i,1));
end
for i=11:12
   leanness_level(i,1)=current_value(i);
   leanness_level(i,2)=(current_value(i)-TFN(i,3))/(TFN(i,3)-TFN(i,1));
   leanness_level(i,3)=TFN(i,2);
   leanness_level(i,4)=(TFN(i,3)-TFN(i,2))/(TFN(i,3)-TFN(i,1));
end
disp('     current        Current      Optimum       optimum')
disp('     metrics        leanness      metric       leanness')
disp('      value          level        value         level')
disp(leanness_level)
```

MATLAB code for contour plot of coefficient correlation:

```
ManufactruingCost=[20 27 25 35 30 55 40 38];
TotalIventorycost=[10 12 15 20 18 25 22 13];
TransportationCost=[12 18 20 15 25 30 21 35];
LeadTime=[130 135 132 140 145 143 150 160];
SetupTime=[20 21 22 25 26 27 40 32];
LaborProductivity=[13 8 9 11 12 7 9 12];
OEE=[82 76 78 56 60 59 85 84];
RejectRate=[7 7 8 10 12 13 14 20];
ReworkRate=[5 5.5 7 9 13 9.5 11.5 20];
CustomerSatisfaction=[90 65 70 75 80 80 85 50];
TechUsage=[65 70 70 75 78 90 90 85];
SupplierResponsiveness=[60 62 65 69 78 90 88 85];
OntimeDelivery=[60 62 65 68 75 82 78 82];
NumberOFWorkRelatedInjuries=[3 3 4 6 5 7 8 10];
A=[ManufactruingCost;TotalIventorycost;TransportationCost;LeadTime;SetupTime;LaborProductivity;OEE;Reject
Rate;ReworkRate;CustomerSatisfaction;TechUsage;SupplierResponsiveness;OntimeDelivery;NumberOFWorkRelat
edInjuries];
B=A';
X=corrcoef(B)

% Eliminate symmetry and diagonal from analysis
for i = 1:size(X,1)
    for j = 1:i
        X(i,j)=0;
    end
end

close all
threshold_val = 0:0.1:0.9;
threshold_store = [];
count = 0;
for k = 1:length(threshold_val)
    threshold = threshold_val(k);
    % Make list of pairs
    [i,j] = find(abs(X) > threshold);
    threshold
    [i,j]
    count = count+1;
    if count == 1
        threshold_store = [i,j];
    else

        threshold_store(1:length(i),:,count) = [i,j];
    end

    % Image the relationships
    figure
    contour(X',threshold:0.01:1);
    colorbar

    temp = get(gca,'xlim');
    set(gca,'xtick',temp(1):temp(2))
    temp = get(gca,'ylim');
```

```
    set(gca,'ytick',temp(1):temp(2))
    axis equal
    grid
    xlabel('Fourteen performance metrics')
    ylabel('Fourteen performance metrics')


end
```

Appendix I

To obtain $\mathbf{w_1}$,

The overall leanness index	Financial	Productivity	Quality	Safety	Flexibility
Financial	(1, 1, 1)	(1 , 2, 3)	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
Productivity		(1, 1, 1)	(1 , 2, 3)	(2, 3, 4)	(1 , 2, 3)
Quality			(1, 1, 1)	(2, 3, 4)	(1 , 2, 3)
Safety				(1, 1, 1)	(1 , 2, 3)
Flexibility					(1, 1, 1)

To obtain $\mathbf{w_2}$,

Financial	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1,2,3)	(5,6,7)	(3,4,5)	(7,8,9)	(3,4,5)	(2,3,4)	(6,7,8)	(5,6,7)	(4,5,6)	(5,6,7)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(3,4,5)	(4,5,6)	(5,6,7)	(3,4,5)	(4,5,6)	(5,6,7)	(6,7,8)	(4,5,6)	(6,7,8)	0.22
Transportation cost			(1,1,1)	(4,5,6)	(2,3,4)	(6,7,8)	(4,5,6)	(2,3,4)	(5,6,7)	5,6,7)	6,7,8)	(4,5,6)	0.20
Setup time				(1,1,1)	1,2,3)	(5,6,7)	(2,3,4)	(3,4,5)	(6,7,8)	(7,8,9)	(4,5,6)	(2,3,4)	0.14
Manufacturing lead time					(1,1,1)	(5,6,7)	(2,3,4)	(2,3,4)	(5,6,7)	(6,7,8)	(4,5,6)	(1,2,3)	0.11
Labour productivity						(1,1,1)	(1/4,1/3,1/2)	(1,2,3)	(4,5,6)	(3,4,5)	(2,3,4)	(1/5,1/4,1/3)	0
Overall equipment efficiency							(1,1,1)	(3,4,5)	(5,6,7)	(6,7,8)	(5,6,7)	(1,2,3)	0.07
Rework rate								(1,1,1)	(3,4,5)	(6,7,8)	(2,3,4)	(1/6,1/5,1/4)	0
Customer satisfaction									(1,1,1)	(3,4,5)	(2,3,4)	(1/5,1/4,1/3)	0
No. of work-related injuries										(1,1,1)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	0
Supplier responsiveness											(1,1,1)	(1/3,1/2.1)	0
On-time delivery												(1,1,1)	0.03

Productivity	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1,2,3)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/3,1/2,1)	(1/5,1/4,1/3)	(1,2,3)	(3,4,5)	(6,7,8)	(3,4,5)	(2,3,4)	0.23
Total inventory cost		(1,1,1)	(1,1,1)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(1/3,1/2.1)	(1/6,1/5,1/4)	(1,2,3)	(3,4,5)	(2,3,4)	(3,4,5)	(1/4,1/3,1/2)	0.22
Transportation cost			(1,1,1)	(1/7,1/6,1/5)	(1/3,1/2,1)	(1/3,1/2,1)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(3,4,5)	(2,3,4)	(3,4,5)	(1,2,3)	0.20
Setup time				(1,1,1)	(2,3,4)	(4,5,6)	(2,3,4)	(6,7,8)	(5,6,7)	(6,7,8)	(3,4,5)	(3,4,5)	0.14
Manufacturing lead time					(1,1,1)	(3,4,5)	(2,3,4)	(2,3,4)	(4,5,6)	(3,4,5)	(5,6,7)	(3,4,5)	0.11
Labour productivity						(1,1,1)	(1,2,3)	(4,5,6)	(5,6,7)	(5,6,7)	(6,7,8)	(3,4,5)	0
Overall equipment efficiency							(1,1,1)	(6,7,8)	(5,6,7)	(6,7,8)	(4,5,6)	(3,4,5)	0.07
Rework rate								(1,1,1)	(5,6,7)	(4,5,6)	(2,3,4)	(2,3,4)	0
Customer satisfaction									(1,1,1)	(4,5,6)	(4,5,6)	(1,2,3)	0
No. of work-related injuries										(1,1,1)	(1/3,1/2.1)	(1/6,1/5,1/4)	0
Supplier responsiveness											(1,1,1)	(1/4,1/3,1/2)	0
On-time delivery												(1,1,1)	0.03

Quality	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,1,1)	(1,1,1)	(2,3,4)	(1,2,3)	(3,4,5)	(1/4,1/3,1/2)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	(4,5,6)	(3,4,5)	(3,4,5)	0.23
Total inventory cost		(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(2,3,4)	(1/6,1/5,1/4)	(1/6,1/5,1/4)	(2,3,4)	(3,4,5)	(1,2,3)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(1,2,3)	(3,4,5)	(1,2,3)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(5,6,7)	(3,4,5)	(2,3,4)	0.20
Setup time				(1,1,1)	(1,2,3)	(3,4,5)	(5,6,7)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(6,7,8)	(3,4,5)	(1,2,3)	0.14
Manufacturing lead time					(1,1,1)	(3,4,5)	(2,3,4)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(6,7,8)	(3,4,5)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(1,2,3)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	(1,1,1)	(2,3,4)	(1/3,1/2.1)	0
Overall equipment efficiency							(1,1,1)	(1/7,1/6,1/5)	(1/7,1/6,1/5)	(4,5,6)	(3,4,5)	(1,2,3)	0.07
Rework rate								(1,1,1)	(1,2,3)	(1/5,1/4,1/3)	(1/5,1/4,1/3)	(1/7,1/6,1/5)	0
Customer satisfaction									(1,1,1)	(1/8,1/7,1/6)	(1/4,1/3,1/2)	(1/3,1/2.1)	0
No. of work-related injuries										(1,1,1)	(1/4,1/3,1/2)	(1/3,1/2,1)	0
Supplier responsiveness											(1,1,1)	(1,2,3)	0
On-time delivery												(1,1,1)	0.03

Safety	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(1,2,3)	(3,4,5)	(5,6,7)	(1/4,1/3,1/2)	(3,4,5)	(2,3,4)	0.23
Total inventory cost		(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(3,4,5)	(2,3,4)	(1,2,3)	(3,4,5)	(1/4,1/3,1/2)	(2,3,4)	(2,3,4)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(1,2,3)	(3,4,5)	(2,3,4)	(3,4,5)	(4,5,6)	(1/6,1/5,1/4)	(4,5,6)	(1,1,1)	0.20
Setup time				(1,1,1)	(3,4,5)	(2,3,4)	(2,3,4)	(5,6,7)	(5,6,7)	(1/4,1/3,1/2)	(3,4,5)	(2,3,4)	0.14
Manufacturing lead time					(1,1,1)	(3,4,5)	(2,3,4)	(2,3,4)	(1,2,3)	(1/7,1/6,1/5)	(2,3,4)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(1/3,1/2,1)	(1,2,3)	(2,3,4)	(1/8,1/7,1/6)	(1/3,1/2.1)	(1/3,1/2,1)	0
Overall equipment efficiency							(1,1,1)	(2,3,4)	(3,4,5)	(1/6,1/5,1/4)	(2,3,4)	(1/4,1/3,1/2)	0.07
Rework rate								(1,1,1)	(2,3,4)	(1/7,1/6,1/5)	(3,4,5)	(1,2,3)	0
Customer satisfaction									(1,1,1)	(1/9,1/8,1/7)	(1,2,3)	(1,1,1)	0
No. of work-related injuries										(1,1,1)	(5,6,7)	(4,5,6)	0
Supplier responsiveness											(1,1,1)	(1,2,3)	0
On-time delivery												(1,1,1)	0.03

Flexibility	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(3,4,5)	(2,3,4)	(4,5,6)	(5,6,7)	(3,4,5)	(1/6,1/5,1/4)	(1/9,1/8,1/7)	0.23
Total inventory cost		(1,1,1)	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(2,3,4)	(3,4,5)	(4,5,6)	(4,5,6)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	0.22
Transportation cost			(1,1,1)	(2,3,4)	(1,1,1)	(2,3,4)	(3,4,5)	(2,3,4)	(2,3,4)	(3,4,5)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	0.20
Setup time				(1,1,1)	(2,3,4)	(4,5,6)	(2,3,4)	(3,4,5)	(5,6,7)	(6,7,8)	(1/8,1/7,1/6)	(1/5,1/4,1/3)	0.14
Manufacturing lead time					(1,1,1)	(3,4,5)	(4,5,6)	(2,3,4)	(1,2,3)	(5,6,7)	(1/4,1/3,1/2)	(1/3,1/2,1)	0.11
Labour productivity						(1,1,1)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	(1,2,3)	(1,1,1)	(1/7,1/6,1/5)	(1/8,1/7,1/6)	0
Overall equipment efficiency							(1,1,1)	(2,3,4)	(3,4,5)	(5,6,7)	(1/8,1/7,1/6)	(1/7,1/6,1/5)	0.07
Rework rate								(1,1,1)	(2,3,4)	(4,5,6)	(1/7,1/6,1/5)	(1/6,1/5,1/4)	0
Customer satisfaction									(1,1,1)	(2,3,4)	(1/7,1/6,1/5)	(1/3,1/2,1)	0
No. of work-related injuries										(1,1,1)	(1/8,1/7,1/6)	(1/8,1/7,1/6)	0
Supplier responsiveness											(1,1,1)	(1,2,3)	0
On-time delivery												(1,1,1)	0.03

To obtain $\mathbf{w_3}$,

Financial	Financial	Productivity	Quality	Safety	Flexibility
Financial	(1,1,1)	(4,5,6)	(4,5,6)	(7,8,9)	(5,6,7)
Productivity		(1,1,1)	(3,4,5)	(5,6,7)	(1,2,3)
Quality			(1,1,1)	(3,4,5)	(2,3,4)
Safety				(1,1,1)	(1/4,1/3,1/2)
Flexibility					(1,1,1)
Productivity	Financial	Productivity	Quality	Safety	Flexibility
Financial	(1,1,1)	(1/4,1/3,1/2)	(2,3,4)	(3,4,5)	(2,3,4)
Productivity		(1,1,1)	(5,6,7)	(6,7,8)	(3,4,5)
Quality			(1,1,1)	(3,4,5)	(2,3,4)
Safety				(1,1,1)	(1,2,3)
Flexibility					(1,1,1)
Quality	Financial	Productivity	Quality	Safety	Flexibility
Financial	(1,1,1)	(1,2,3)	(1/4,1/3,1/2)	(3,4,5)	(2,3,4)
Productivity		(1,1,1)	(1/5,1/4,1/3)	(2,3,4)	(1,2,3)
Quality			(1,1,1)	(5,6,7)	(3,4,5)

Safety				(1,1,1)	(1,2,3)
Flexibility					(1,1,1)
Safety	Financial	Productivity	Quality	Safety	Flexibility
Financial	(1,1,1)	(2,3,4)	(2,3,4)	(1/5,1/4,1/3)	(3,4,5)
Productivity		(1,1,1)	(2,3,4)	(1/4,1/3,1/2)	(2,3,4)
Quality			(1,1,1)	(1/4,1/3,1/2)	(2,3,4)
Safety				(1,1,1)	(4,5,6)
Flexibility					(1,1,1)
Flexibility	Financial	Productivity	Quality	Safety	Flexibility
Financial	(1,1,1)	(1,2,3)	(2,3,4)	(4,5,6)	(1/3,1/2.1)
Productivity		(1,1,1)	(1,2,3)	(3,4,5)	(1/4,1/3,1/2)
Quality			(1,1,1)	(4,5,6)	(1/5,1/4,1/3)
Safety				(1,1,1)	(1/7,1/6,1/5)
Flexibility					(1,1,1)

To obtain $\mathbf{w_4}$,

Cost per part	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(3,4,5)	(2,3,4)	(4,5,6)	(3,4,5)	(7,8,9)	(4,5,6)	(2,3,4)	(4,5,6)	(5,6,7)	(3,4,5)	(2,3,4)	0.23
Total inventory cost		(1,1,1)	(2,3,4)	(3,4,5)	(2,3,4)	(3,4,5)	(4,5,6)	(5,6,7)	(4,5,6)	(4,5,6)	(4,5,6)	(3,4,5)	0.22
Transportation cost			(1,1,1)	(4,5,6)	(3,4,5)	(5,6,7)	(5,6,7)	(4,5,6)	(2,3,4)	(3,4,5)	(3,4,5)	(1,2,3)	0.20
Setup time				(1,1,1)	(2,3,4)	(2,3,4)	(2,3,4)	(3,4,5)	(4,5,6)	(3,4,5)	(2,3,4)	(2,3,4)	0.14
Manufacturing lead time					(1,1,1)	(3,4,5)	(3,4,5)	(4,5,6)	(1,2,3)	(4,5,6)	(2,3,4)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(3,4,5)	(2,3,4)	(4,5,6)	(3,4,5)	(2,3,4)	(1/4,1/3,1/2)	0
Overall equipment efficiency							(1,1,1)	(2,3,4)	(2,3,4)	(5,6,7)	(1,2,3)	(1,2,3)	0.07
Rework rate								(1,1,1)	(3,4,5)	(3,4,5)	(2,3,4)	(1,2,3)	0
Customer satisfaction									(1,1,1)	(4,5,6)	(2,3,4)	(1,1,1)	0
No. of work-related injuries										(1,1,1)	(1/3,1/2.1)	(1/5,1/4,1/3)	0
Supplier responsiveness											(1,1,1)	(1,2,3)	0
On-time delivery												(1,1,1)	0.03

Total inventory cost	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1/5,1/4,1/3)	(2,3,4)	(4,5,6)	(3,4,5)	(6,7,8)	(3,4,5)	(1,2,3)	(4,5,6)	(4,5,6)	(3,4,5)	(1,2,3)	0.23
Total inventory cost		(1,1,1)	(2,3,4)	(2,3,4)	(4,5,6)	(3,4,5)	(3,4,5)	(4,5,6)	(3,4,5)	(4,5,6)	(2,3,4)	(2,3,4)	0.22
Transportation cost			(1,1,1)	(3,4,5)	(3,4,5)	(4,5,6)	(5,6,7)	(3,4,5)	(1,2,3)	(3,4,5)	(2,3,4)	(1,2,3)	0.20
Setup time				(1,1,1)	(2,3,4)	(2,3,4)	(2,3,4)	(3,4,5)	(3,4,5)	(3,4,5)	(2,3,4)	(2,3,4)	0.14
Manufacturing lead time					(1,1,1)	(3,4,5)	(3,4,5)	(4,5,6)	(1,2,3)	(4,5,6)	(2,3,4)	(1,2,3)	0.11
Labour productivity						(1,1,1)	(2,3,4)	(1,2,3)	(3,4,5)	(3,4,5)	(2,3,4)	(1/3,1/2.1)	0
Overall equipment efficiency							(1,1,1)	(2,3,4)	(2,3,4)	(5,6,7)	(1,2,3)	(1,2,3)	0.07
Rework rate								(1,1,1)	(3,4,5)	(4,5,6)	(2,3,4)	(1,2,3)	0
Customer satisfaction									(1,1,1)	(3,4,5)	(3,4,5)	(1,1,1)	0
No. of work-related injuries										(1,1,1)	(1/3,1/2.1)	(1/4,1/3,1/2)	0
Supplier responsiveness											(1,1,1)	(2,3,4)	0
On-time delivery												(1,1,1)	0.03

Transportation cost	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1/4,1/3,1/2)	(3,4,5)	(2,3,4)	(4,5,6)	(3,4,5)	(2,3,4)	(4,5,6)	(5,6,7)	(2,3,4)	(2,3,4)	0.23
Total inventory cost		(1,1,1)	(1/4,1/3,1/2)	(2,3,4)	(4,5,6)	(4,5,6)	(3,4,5)	(4,5,6)	(3,4,5)	(4,5,6)	(2,3,4)	(2,3,4)	0.22
Transportation cost			(1,1,1)	(4,5,6)	(5,6,7)	(6,7,8)	(5,6,7)	(5,6,7)	(1,2,3)	(4,5,6)	(4,5,6)	(1,2,3)	0.20
Setup time				(1,1,1)	(1/4,1/3,1/2)	(5,6,7)	(4,5,6)	(4,5,6)	(2,3,4)	(3,4,5)	(3,4,5)	(1,2,3)	0.14
Manufacturing lead time					(1,1,1)	(4,5,6)	(3,4,5)	(2,3,4)	(1,2,3)	(4,5,6)	(2,3,4)	(1,2,3)	0.11
Labour productivity						(1,1,1)	(2,3,4)	(2,3,4)	(1,2,3)	(2,3,4)	(2,3,4)	(1/3,1/2.1)	0
Overall equipment efficiency							(1,1,1)	(2,3,4)	(2,3,4)	(5,6,7)	(1,2,3)	(1/4,1/3,1/2)	0.07
Rework rate								(1,1,1)	(3,4,5)	(4,5,6)	(2,3,4)	(1/6,1/5,1/4)	0
Customer satisfaction									(1,1,1)	(3,4,5)	(3,4,5)	(1,1,1)	0
No. of work-related injuries										(1,1,1)	(1/3,1/2.1)	(1/4,1/3,1/2)	0
Supplier responsiveness											(1,1,1)	(1/3,1/2.1)	0
On-time delivery												(1,1,1)	0.03

Setup time	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1,2,3)	(1/4,1/3,1/2)	(1,2,3)	(3,4,5)	(2,3,4)	(2,3,4)	(4,5,6)	(5,6,7)	(2,3,4)	(2,3,4)	0.23
Total inventory cost		(1,1,1)	(2,3,4)	(1/5,1/4,1/3)	(4,5,6)	(4,5,6)	(3,4,5)	(4,5,6)	(3,4,5)	(4,5,6)	(2,3,4)	(2,3,4)	0.22
Transportation cost			(1,1,1)	(1/6,1/5,1/4)	(5,6,7)	(6,7,8)	(5,6,7)	(5,6,7)	(1,2,3)	(4,5,6)	(4,5,6)	(1,2,3)	0.20
Setup time				(1,1,1)	(1,2,3)	(4,5,6)	(3,4,5)	(4,5,6)	(3,4,5)	(4,5,6)	(3,4,5)	(2,3,4)	0.14
Manufacturing lead time					(1,1,1)	(4,5,6)	(3,4,5)	(2,3,4)	(1,2,3)	(4,5,6)	(2,3,4)	(1,2,3)	0.11
Labour productivity						(1,1,1)	(2,3,4)	(2,3,4)	(3,4,5)	(3,4,5)	(2,3,4)	(2,3,4)	0
Overall equipment efficiency							(1,1,1)	(2,3,4)	(2,3,4)	(5,6,7)	(1,2,3)	(1/4,1/3,1/2)	0.07
Rework rate								(1,1,1)	(3,4,5)	(4,5,6)	(2,3,4)	(1/6,1/5,1/4)	0
Customer satisfaction									(1,1,1)	(3,4,5)	(3,4,5)	(1,1,1)	0
No. of work-related injuries										(1,1,1)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	0
Supplier responsiveness											(1,1,1)	(1/3,1/2,1)	0
On-time delivery												(1,1,1)	0.03

Manufacturing lead time	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1,2,3)	(1/4,1/3,1/2)	(1/6,1/5,1/4)	(3,4,5)	(2,3,4)	(2,3,4)	(4,5,6)	(5,6,7)	(2,3,4)	(2,3,4)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(1/5,1/4,1/3)	(1/7,1/6,1/5)	(4,5,6)	(3,4,5)	(4,5,6)	(3,4,5)	(4,5,6)	(2,3,4)	(2,3,4)	0.22
Transportation cost			(1,1,1)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(6,7,8)	(5,6,7)	(5,6,7)	(1,2,3)	(4,5,6)	(4,5,6)	(1,2,3)	0.20
Setup time				(1,1,1)	(1,1,1)	(4,5,6)	(3,4,5)	(4,5,6)	(3,4,5)	(4,5,6)	(3,4,5)	(2,3,4)	0.14
Manufacturing lead time					(1,1,1)	(5,6,7)	(4,5,6)	(2,3,4)	(3,4,5)	(4,5,6)	(2,3,4)	(1,2,3)	0.11
Labour productivity						(1,1,1)	(1,2,3)	(1,2,3)	(3,4,5)	(3,4,5)	(2,3,4)	(2,3,4)	0
Overall equipment efficiency							(1,1,1)	(2,3,4)	(3,4,5)	(5,6,7)	(1,2,3)	(1/4,1/3,1/2)	0.07
Rework rate								(1,1,1)	(2,3,4)	(3,4,5)	(2,3,4)	(1/5,1/4,1/3)	0
Customer satisfaction									(1,1,1)	(2,3,4)	(3,4,5)	(1/4,1/3,1/2)	0
No. of work-related injuries										(1,1,1)	(1/4,1/3,1/2)	(1/4,1/3,1/2)	0
Supplier responsiveness											(1,1,1)	(1/3,1/2,1)	0
On-time delivery												(1,1,1)	0.03

Labour productivity	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)	(2,3,4)	(1/4,1/3,1/2)	(3,4,5)	(4,5,6)	(2,3,4)	(3,4,5)	(3,4,5)	(2,3,4)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(2,3,4)	(1,2,3)	(1/5,1/4,1/3)	(3,4,5)	(2,3,4)	(3,4,5)	(3,4,5)	(3,4,5)	(2,3,4)	0.22
Transportation cost			(1,1,1)	(3,4,5)	(2,3,4)	(1/6,1/5,1/4)	(1,2,3)	(2,3,4)	(1,2,3)	(1,2,3)	(2,3,4)	(1,2,3)	0.20
Setup time				(1,1,1)	(1,1,1)	(1/5,1/4,1/3)	(1,2,3)	(1,2,3)	(3,4,5)	(2,3,4)	(3,4,5)	(1,2,3)	0.14
Manufacturing lead time					(1,1,1)	(1/4,1/3,1/2)	(2,3,4)	(3,4,5)	(1,2,3)	(2,3,4)	(2,3,4)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(3,4,5)	(2,3,4)	(4,5,6)	(2,3,4)	(4,5,6)	(2,3,4)	0
Overall equipment efficiency							(1,1,1)	(1,2,3)	(3,4,5)	(2,3,4)	(2,3,4)	(1,2,3)	0.07
Rework rate								(1,1,1)	(4,5,6)	(3,4,5)	(4,5,6)	(2,3,4)	0
Customer satisfaction									(1,1,1)	(1/3,1/2,1)	(2,3,4)	(1,1,1)	0
No. of work-related injuries										(1,1,1)	(3,4,5)	(2,3,4)	0
Supplier responsiveness											(1,1,1)	(1/4,1/3,1/2)	0
On-time delivery												(1,1,1)	0.03

Overall equipment efficiency	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(2,3,4)	(1,2,3)	(1,2,3)	(1,2,3)	(3,4,5)	(1/4,1/3,1/2)	(4,5,6)	(2,3,4)	(4,5,6)	(2,3,4)	(3,4,5)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(1/4,1/3,1/2)	(2,3,4)	(1/3,1/2,1)	(1/5,1/4,1/3)	(3,4,5)	(3,4,5)	(5,6,7)	(2,3,4)	(3,4,5)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(2,3,4)	(3,4,5)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(2,3,4)	(3,4,5)	(3,4,5)	(2,3,4)	0.20
Setup time				(1,1,1)	(1,2,3)	(1,2,3)	(1/5,1/4,1/3)	(1,2,3)	(3,4,5)	(4,5,6)	(5,6,7)	(1,2,3)	0.14
Manufacturing lead time					(1,1,1)	(2,3,4)	(1/4,1/3,1/2)	(1,2,3)	(2,3,4)	(3,4,5)	(1,2,3)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(1/7,1/6,1/5)	(1,2,3)	(5,6,7)	(1,1,1)	(1,2,3)	(1,2,3)	0
Overall equipment efficiency							(1,1,1)	(2,3,4)	(6,7,8)	(5,6,7)	(5,6,7)	(3,4,5)	0.07
Rework rate								(1,1,1)	(4,5,6)	(5,6,7)	(3,4,5)	(1,2,3)	0
Customer satisfaction									(1,1,1)	(3,4,5)	(3,4,5)	(1/4,1/3,1/2)	0
No. of work-related injuries										(1,1,1)	(1,2,3)	(1,2,3)	0
Supplier responsiveness											(1,1,1)	(1/6,1/5,1/4)	0
On-time delivery												(1,1,1)	0.03

Rework rate	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1,2,3)	(1,2,3)	(1,2,3)	(4,5,6)	(2,3,4)	(1/3,1/2,1)	(2,3,4)	(4,5,6)	(2,3,4)	(3,4,5)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(3,4,5)	(2,3,4)	(1,2,3)	(2,3,4)	(1/5,1/4,1/3)	(3,4,5)	(4,5,6)	(2,3,4)	(3,4,5)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(2,3,4)	(3,4,5)	(3,4,5)	(1/7,1/6,1/5)	(2,3,4)	(2,3,4)	(3,4,5)	(2,3,4)	0.20
Setup time				(1,1,1)	(1,2,3)	(1,2,3)	(1,2,3)	(1/4,1/3,1/2)	(3,4,5)	(3,4,5)	(5,6,7)	(1,2,3)	0.14
Manufacturing lead time					(1,1,1)	(2,3,4)	(3,4,5)	(1/4,1/3,1/2)	(2,3,4)	(3,4,5)	(1,2,3)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(1/3,1/2,1)	(1/5,1/4,1/3)	(5,6,7)	(1,2,3)	(1,2,3)	(1,2,3)	0
Overall equipment efficiency							(1,1,1)	(1/4,1/3,1/2)	(6,7,8)	(4,5,6)	(5,6,7)	(3,4,5)	0.07
Rework rate								(1,1,1)	(5,6,7)	(4,5,6)	(3,4,5)	(2,3,4)	0
Customer satisfaction									(1,1,1)	(2,3,4)	(3,4,5)	(1/4,1/3,1/2)	0
No. of work-related injuries										(1,1,1)	(1,2,3)	(1/3,1/2,1)	0
Supplier responsiveness											(1,1,1)	(1,1,1)	0
On-time delivery												(1,1,1)	0.03

Customer satisfaction	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(3,4,5)	(1,2,3)	(2,3,4)	(1,2,3)	(4,5,6)	(2,3,4)	(2,3,4)	(1/4,1/3,1/2)	(4,5,6)	(3,4,5)	(1,2,3)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(3,4,5)	(2,3,4)	(1,2,3)	(2,3,4)	(2,3,4)	(1/7,1/6,1/5)	(4,5,6)	(2,3,4)	(3,4,5)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(2,3,4)	(3,4,5)	(3,4,5)	(5,6,7)	(1/5,1/4,1/3)	(2,3,4)	(4,5,6)	(2,3,4)	0.20
Setup time				(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(1,2,3)	(1/8,1/7,1/6)	(3,4,5)	(4,5,6)	(1/5,1/4,1/3)	0.14
Manufacturing lead time					(1,1,1)	(2,3,4)	(3,4,5)	(6,7,8)	(1/3,1/2,1)	(3,4,5)	(1,2,3)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(1/3,1/2,1)	(2,3,4)	(1/6,1/5,1/4)	(1,2,3)	(1,2,3)	(1/5,1/4,1/3)	0
Overall equipment efficiency							(1,1,1)	(1,2,3)	(1/7,1/6,1/5)	(4,5,6)	(5,6,7)	(3,4,5)	0.07
Rework rate								(1,1,1)	(1/6,1/5,1/4)	(3,4,5)	(1,2,3)	(1/5,1/4,1/3)	0
Customer satisfaction									(1,1,1)	(5,6,7)	(4,5,6)	(2,3,4)	0
No. of work-related injuries										(1,1,1)	(1/4,1/3,1/2)	(1/5,1/4,1/3)	0
Supplier responsiveness											(1,1,1)	(1/4,1/3,1/2)	0
On-time delivery												(1,1,1)	0.03

Number of work-related injuries	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)	(1,2,3)	(2,3,4)	(2,3,4)	(2,3,4)	(2,3,4)	(1/4,1/3,1/2)	(3,4,5)	(1,2,3)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(3,4,5)	(2,3,4)	(1,2,3)	(2,3,4)	(2,3,4)	(3,4,5)	(1/4,1/3,1/2)	(2,3,4)	(3,4,5)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(2,3,4)	(3,4,5)	(3,4,5)	(5,6,7)	(2,3,4)	(1/5,1/4,1/3)	(4,5,6)	(2,3,4)	0.20
Setup time				(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(1,2,3)	(4,5,6)	(1/6,1/5,1/4)	(4,5,6)	(1/5,1/4,1/3)	0.14
Manufacturing lead time					(1,1,1)	(2,3,4)	(3,4,5)	(6,7,8)	(1,1,1)	(1/4,1/3,1/2)	(1,2,3)	(1,2,3)	0.11
Labour productivity						(1,1,1)	(2,3,4)	(3,4,5)	(4,5,6)	(1/3,1/2,1)	(2,3,4)	(3,4,5)	0
Overall equipment efficiency							(1,1,1)	(1,2,3)	(1,2,3)	(1/5,1/4,1/3)	(5,6,7)	(2,3,4)	0.07
Rework rate								(1,1,1)	(1,2,3)	(1/5,1/4,1/3)	(1,2,3)	(1/5,1/4,1/3)	0
Customer satisfaction									(1,1,1)	(1/6,1/5,1/4)	(1,2,3)	(1/5,1/4,1/3)	0
No. of work-related injuries										(1,1,1)	(4,5,6)	(5,6,7)	0
Supplier responsiveness											(1,1,1)	(1/4,1/3,1/2)	0
On-time delivery												(1,1,1)	0.03

Supplier responsiveness	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(2,3,4)	(3,4,5)	(2,3,4)	(2,3,4)	(3,4,5)	(4,5,6)	(1/4,1/3,1/2)	(1,2,3)	0.23
Total inventory cost		(1,1,1)	(1,2,3)	(1,2,3)	(1,2,3)	(2,3,4)	(3,4,5)	(3,4,5)	(4,5,6)	(4,5,6)	(1/5,1/4,1/3)	(1/3,1/2,1)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(2,3,4)	(3,4,5)	(2,3,4)	(4,5,6)	(4,5,6)	(5,6,7)	(1/4,1/3,1/2)	(1,2,3)	0.20
Setup time				(1,1,1)	(1,1,1)	(2,3,4)	(2,3,4)	(3,4,5)	(4,5,6)	(4,5,6)	(1/5,1/4,1/3)	(2,3,4)	0.14
Manufacturing lead time					(1,1,1)	(3,4,5)	(2,3,4)	(3,4,5)	(4,5,6)	(4,5,6)	(1/5,1/4,1/3)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1)	(3,4,5)	(1/6,1/5,1/4)	(1/5,1/4,1/3)	0
Overall equipment efficiency							(1,1,1)	(1,1,1)	(3,4,5)	(4,5,6)	(1/5,1/4,1/3)	(1/4,1/3,1/2)	0.07
Rework rate								(1,1,1)	(2,3,4)	(2,3,4)	(1/6,1/5,1/4)	(1,2,3)	0
Customer satisfaction									(1,1,1)	(4,5,6)	(1/7,1/6,1/5)	(1,2,3)	0
No. of work-related injuries										(1,1,1)	(1/9,1/8,1/7)	(1/6,1/5,1/4)	0
Supplier responsiveness											(1,1,1)	(2,3,4)	0
On-time delivery												(1,1,1)	0.03

On-time delivery	Cost per part	Total inventory cost	Transportation cost	Setup time	Manufacturing lead time	Labour productivity	Overall equipment efficiency	Rework rate	Customer satisfaction	No. of work-related injuries	Supplier responsiveness	On-time delivery	Relative importance weightings
Cost per part	(1,1,1)	(1,2,3)	(1,2,3)	(2,3,4)	(1/4,1/3,1/2)	(2,3,4)	(2,3,4)	(4,5,6)	(4,5,6)	(5,6,7)	(2,3,4)	(1/4,1/3,1/2)	0.23
Total inventory cost		(1,1,1)	(2,3,4)	(1,2,3)	(1/5,1/4,1/3)	(2,3,4)	(2,3,4)	(3,4,5)	(3,4,5)	(6,7,8)	(2,3,4)	(1/4,1/3,1/2)	0.22
Transportation cost			(1,1,1)	(1,2,3)	(1,1,1)	(1,2,3)	(2,3,4)	(2,3,4)	(3,4,5)	(4,5,6)	(1,2,3)	(1/5,1/4,1/3)	0.20
Setup time				(1,1,1)	(1/4,1/3,1/2)	(3,4,5)	(2,3,4)	(2,3,4)	(2,3,4)	(4,5,6)	(4,5,6)	(1/4,1/3,1/2)	0.14
Manufacturing lead time					(1,1,1)	(6,7,8)	(3,4,5)	(3,4,5)	(6,7,8)	(5,6,7)	(2,3,4)	(1,1,1)	0.11
Labour productivity						(1,1,1)	(1,2,3)	(1,2,3)	(4,5,6)	(5,6,7)	(2,3,4)	(1/4,1/3,1/2)	0
Overall equipment efficiency							(1,1,1)	(1,2,3)	(4,5,6)	(4,5,6)	(1,2,3)	(1/5,1/4,1/3)	0.07
Rework rate								(1,1,1)	(3,4,5)	(3,4,5)	(2,3,4)	(1/5,1/4,1/3)	0
Customer satisfaction									(1,1,1)	(3,4,5)	(2,3,4)	(1/3,1/2,1)	0
No. of work-related injuries										(1,1,1)	(1/5,1/4,1/3)	(1/6,1/5,1/4)	0
Supplier responsiveness											(1,1,1)	(1/4,1/3,1/2)	0
On-time delivery												(1,1,1)	0.03