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# A Multi-Objective Methodology for Selecting Lean Initiatives in Modular Construction Companies

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***Abstract*****—**The implementation of lean manufacturing initiatives has produced significant impacts in improving operational performance and reducing manufacturing wastes in the production process. However, selecting an appropriate set of lean strategies is critical to avoid misapplication of the lean manufacturing techniques and consequential increase in non-value-adding activities. To the author's best knowledge, there is currently no methodology to select lean strategies that considers their impacts on manufacturing wastes and performance metrics simultaneously. In this research, a multi-objective methodology is proposed that suggests an appropriate set of lean initiatives based on their impacts on performance metrics and manufacturing wastes and within manufacturers' resource limitation. The proposed methodology in this research suggests the best set of lean initiatives for implementation that have highest impacts on identified critical performance metrics and manufacturing wastes. Therefore, manufacturers can assure that implementing suggested lean tools improves their production performance and reduces manufacturing wastes at the same time. A case study was conducted to show the effectiveness and validate the proposed model and methodologies.

***Keywords*****—**Lean manufacturing, Lean strategies, manufacturing wastes, manufacturing performance metrics, decision making, optimisation.

## I. Introduction

SELECTING the appropriate lean tools for implementation 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 organisation and production problem [1]. Although there are several success stories, many lean implementation projects failed due to misapplication of various lean tools in terms of choosing 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 labours' productivity [2]. Therefore, researchers have developed several approaches for selecting the most appropriate lean techniques to eliminate manufacturing wastes and improve production performance [2]-[8]. 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 initiatives on the performance metrics and identified wastes to select the best lean strategies and avoid incorrect application of lean strategies [9]. In this regard, several research studies were conducted to develop different methodologies for selecting lean strategies according to the organisation requirements. In a few methods published, the relationships between lean tools and manufacturing wastes were considered to select the most appropriate lean strategies to minimise production problems and improve the performance effectively [10]. However, these available methodologies lack an effective approach that consider the relationship between lean tools, the identified manufacturing wastes and performance metrics simultaneously to suggest the most appropriate lean strategies that address both the critical performance metrics and wastes.

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## II. Literature Review

### *A. History of Lean Production System*

After World War II, manufacturing companies were faced significant shortage of material, labour and financial resources. Therefore, Japanese manufacturers had a challenge to compete 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 Toyota company developed a new process-oriented system, known as the Toyota Production System (TPS) or Lean manufacturing. 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. The lean manufacturing systems have been recognised by western manufacturers to be able to compete with Japanese manufacturing companies.

### *B. Historical Development of Lean Initiatives Selection Approaches*

Ayag [11] and Leng, Jiang [12] used Multi-criteria group-based decision making (MCGDM) for the lean initiatives selection problems. This method is significantly influenced by preferences and involved numerous decision-makers and reference standards. In addition, in the other research studies, the Analytical Hierarchy Process (AHP) has been used to select appropriate lean initiatives. Despite considerable achievement of this method, it has been argued that this method uses the same evaluation system to evaluate different alternatives [13]-[16].

In a method proposed by Hines and Rich [4], a methodology for selecting value stream mapping (VSM) tools based on the relationships between VSM tools and production problems was proposed. In this method, the correlation matrix for VSM tools and manufacturing wastes was developed based on managers' opinion and literature review [17]. Prior to this stage, they trained the management team 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 [4] established the interrelationship matrix for VSM tools and manufacturing wastes using the previous literature and mangers' experience. However, their method lacks the analytical approach in selecting the best lean tools, and also their method is limited to the set of VSM tools, and the other lean strategies were ignored.

In another research study, 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, identifies and prioritises potential improvement initiatives for the selection problems [18]. 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' judgements and qualitatively assesses the best improvement initiatives.

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 [3]. However, in this method, only JIT tools were taken into consideration, and the other lean tools were overlooked. Also, their selection processes were limited to 11 scenarios. Moreover, their method did not consider the resource limitation of the manufacturer in selecting the best solutions [19].

Singh and Choudhury [20] improved the above methodology by using multi-attribute utility theory to integrate managers' opinion 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) [20]. The results of this research illustrated that not all VSM tools were required to identify the production wastes. However, similar to the previous research, in their method other lean tools that might be suitable were ignored, and they only focused on VSM tools. Furthermore, in research conducted by Inanjai and Farris [8], a decision support tool for selecting lean tools based on the organisation requirements and their manufacturing wastes was developed. In this research, they 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 [3], [8], [10], [17].

Amin and Karim [6] 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, and also, the manufacturing wastes were prioritised using managers' opinions. Then, they 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 [6]. 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 were not established at the same 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 can assist manufacturers significantly by providing them with the more accurate results [10].

## III. Problem Statement

Many manufacturers choose lean strategies based on their personal judgements without any logical assessment of their sub sequential effects. Therefore, in order to achieve the desired results from lean transformation, it is essential to develop a methodology that suggest the most effective lean tools according to their interrelationships with production problems and performance metrics. A methodology for selecting the best set of lean tools should be developed to avoid an increase in non-value-adding activities caused by misapplication of lean tools. The selected lean tools should result in optimising the improvement of performance metrics and 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.

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.

## IV. Proposed Methodology for Selecting Appropriate Lean Initiatives

In every innovation project, improvement activities should have a contribution toward the organisation 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

[10].

Based on the mathematical model of Gautam and Singh [21], the perceived value index increase of adopting $n$ lean strategies can be measured by (1):

$$perceived\ value\ index\ increase = \sum_{i=1}^{n} L_i\, P_{1i} \quad (1)$$

$L_i$ 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.

In this research study, the benefits of lean strategies implementation for improving performance metrics and reducing manufacturing wastes are assessed by developing the perceived value index. The definition of perceived value is the perception of manufacturers of the value of reducing production wastes and enhancing performance metrics and is evaluated by allocating the relative importance rates to their goal. Therefore, 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 approached developed by Amin [10]. 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 appropriate set of lean strategies.

Previously, the aim of lean strategies selection methodologies was to implement lean tools that help manufacturers in reducing manufacturing wastes. However, this research developed a methodology that suggests 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 manufacturer to implement lean strategies based on different competitive strategies while reducing wastes and optimising their performance. This objective can be translated to the following mathematical equation:

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

$$Minimize\ the\ total\ cost = \left(\left(C_{0_{0i}} + \sum_{i=1}^{n} L_i\, C_{O_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, C_{O_{2ij}}\right) + \left(C_{A_{0i}} + \sum_{i=1}^{n} L_i\, C_{A_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, C_{A_{2ij}}\right) + \left(C_{V_{0i}} + \sum_{i=1}^{n} L_i\, C_{V_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, C_{V_{2ij}}\right) + \left(C_{R_{0i}} + \sum_{i=1}^{n} p(i) L_i\, C_{R_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} p(i) L_i L_j\, C_{R_{2ij}}\right)\right) (3)$$

$$Minimize\ the\ total\ time = \left(\left(T_{P_{0i}} + \sum_{i=1}^{n} L_i\, T_{P_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, T_{P_{2ij}}\right) + \left(T_{T_{0i}} + \sum_{i=1}^{n} L_i\, T_{T_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, T_{T_{2ij}}\right) + \left(T_{D_{0i}} + \sum_{i=1}^{n} L_i\, T_{D_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, T_{D_{2ij}}\right) + \left(T_{V_{0i}} + \sum_{i=1}^{n} L_i\, T_{V_{1i}} + \sum_{i=1}^{n}\sum_{j=1}^{n} L_i L_j\, T_{V_{2ij}}\right)\right) \ (4)$$

In (2), the aim is to maximise the perceived value index of lean strategies implementation for improving performance metrics and reducing wastes. 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 (3) and (4) [10].

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:

$$The\ total\ operating\ cost\ of\ lean\ tools\ implementation \le Operating\ cost\ budget \quad (5)$$

$$The\ total\ amortization\ cost\ of\ lean\ tools\ implementation \le Amortization\ cost\ budget \quad (6)$$

$$The\ total\ variable\ cost\ of\ lean\ tools\ implementation \le Variable\ cost\ budget \quad (7)$$

$$The\ total\ risk\ cost\ of\ lean\ tools\ implementation \le Risk\ cost\ budget \quad (8)$$

$$The\ total\ plannign\ time\ of\ lean\ tools\ implementation \le Planning\ time\ limit \quad (9)$$

$$The\ total\ training\ time\ of\ lean\ tools\ implementation \le Training\ time\ limit \quad (10)$$

$$The\ total\ development\ time\ of\ lean\ tools\ implementation \le Developement\ time\ limit \quad (11)$$

$$The\ total\ validation\ time\ of\ lean\ tools\ implementation \le Validation\ time\ limit \quad (12)$$

## V. Essential Steps of the Proposed Methodology for Selecting Appropriate Set of Lean Initiatives

### A. 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 [22], [23]. In a research study conducted by Dennis and Shook [24], there are 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 [25]. Other researchers added productivity and safety to the metrics [26]. 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.

### B. 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, over processing, unnecessary movements, unnecessary transportation, setup time, knowledge disconnection and defects [4], [6], [22], [27]. After defining the manufacturing wastes, the relative importance values are allocated to each waste by the decision makers in the organisation.

### C. Nominating a Set of Lean Initiatives Based on the Identified Factors and Industry of the Company

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.

### D. The Impacts of Lean Tools on Identified Performance Metrics and Manufacturing Wastes

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 [4] and was used in the previous section to assign the correlation values for lean tools and manufacturing wastes. Therefore, 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 to zero. These relationships and rankings are presented in Table III [4], [6], [17], [20], [24], [28]-[46].

### E. 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 relationship 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 to 1; otherwise it is 0, as presented in Table IV. Establishing a binary correlation matrix simplifies the decision making to suggest proper set of lean tools with the significant influence on identified performance measures. This method can help manufacturers to select a set of lean techniques that have significant relationship with identified wastes. 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.

## VI. Numerical Example

### A. Case Study Company

The HMC[2] 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 strategies in the manufacturing process, such as Cellular Manufacturing and

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

TQM. However, they did not achieve significant benefits from the lean strategies implementation mainly due to 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 participation and involvement of all employees from management level to shop floor staff as well as 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.

### *B. 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 importance for performance metrics. A guideline was provided for them to rank these factors as critical, significant, medium, low or unimportant. The relative importance weights of performance metrics are presented in Table V. The priorities of the decision makers regarding manufacturing wastes reduction are provided in Table VI.

### *C. Establishing Relationship between Lean Strategies, Performance Metrics and Performance Metrics*

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.

Table VI 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 set 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.

### *D. 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 means the level of lean adoption to improve the current manufacturing system. For the purpose of this research low, medium and high are considered as the level of complexity. The lean initiatives implementation cost can be no cost, low cost, moderate cost or high cost. In Table VII, the cost and time units of each lean strategy are presented. These units are estimated from the maximum 10 units.

TABLE I
THE IMPACT OF JIT ON IDENTIFIED PERFORMANCE METRICS

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

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 metrics. Therefore, where JIT, for instance, is selected for implementation the time and cost of implementation using (3)-(12) are as in Table II. In addition, the budget and time allocation constraints of the HMC company are presented in Table IX. 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.

TABLE II
JIT'S IMPLEMENTATION COST AND TIME

| Implementation cost and time lean initiatives | JIT |
|---|---|
| Operating cost | 8 |
| Amortization cost | 4 |
| Variable cost | 3 |
| Risk cost | 7 |
| Planning cost | 6 |
| Training cost | 5 |
| Development cost | 8 |
| Validation cost | 4 |

## VII. DISCUSSION

### *A. 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. 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. A MATLAB program was developed to solve the equations mentioned earlier and 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.

After preparing all 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 output of the model and the analysis of these results show that manufacturer 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.

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), and the minimum perceived value of lean implementation for this company is 6. Table XI 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 12 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 manufacturing wastes of the company.

According to Table XI, JIT impacts on more performance metrics and manufacturing wastes comparing 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 the critical manufacturing wastes identified by the decision makers and top managers. Therefore, application of the 5S principle can help the manufacturer to 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 the 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 the finished product inventories as well as the rework rate.

Table X demonstrates the actual budget and time required for adopting the suggested lean techniques. The next section describes the sensitivity analysis to determine the effect of the dynamic situation in the manufacturing organisation on the result of lean strategies selection method.

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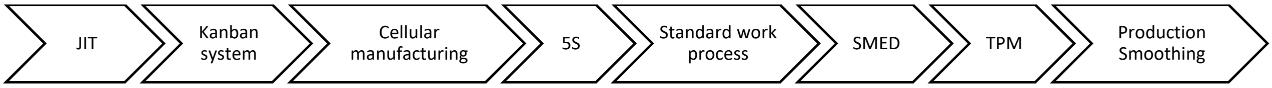


Fig. 1 The sequence of the suggested lean initiatives

TABLE III
IMPACTS OF LEAN INITIATIVES ON PERFORMANCE METRICS AND MANUFACTURING WASTES

| Lean tools | Performance metrics | | Manufacturing wastes |
|---|---|---|---|
| 5S | High correlation | Transportation cost<br>Number of work-related injuries<br>On-time delivery | Unnecessary movement |
| | Medium correlation | Labour productivity<br>Manufacturing lead time | Setup time |
| | Low correlation | Cost per part | Failure time |
| Total Productive maintenance | High correlation | Overall Equipment Efficiency | Failure time |
| | Medium correlation | Labour productivity<br>Rework rate<br>On-time delivery | --- |
| | Low correlation | Manufacturing lead time<br>Customer satisfaction | Defects<br>Setup time |
| Total Quality Management | High correlation | Cost per part<br>Total inventory cost<br>Transportation cost<br>Manufacturing lead time<br>On-time delivery | Final good inventory<br>WIP<br>Raw material inventory |
| | Medium correlation | Supplier responsiveness | --- |
| | Low correlation | --- | Defects |
| Total Quality management | High correlation | Rework rate<br>Customer satisfaction | Defects |
| | Medium correlation | --- | --- |
| | Low correlation | --- | Over processing |
| Kanban system | High correlation | Total inventory cost<br>Setup time<br>On-time delivery | Final good inventory<br>WIP<br>Raw material inventory |
| | Medium correlation | Manufacturing lead time<br>Supplier responsiveness | --- |
| | Low correlation | --- | Defects |
| Production smoothing | High correlation | Rework rate | Final good inventory |
| | Medium correlation | Total inventory cost | WIP<br>Raw material inventory |
| | Low correlation | --- | Defects |
| Standard work process | High correlation | Cost per part<br>Customer satisfaction | Over processing |
| | Medium correlation | Transportation cost | Unnecessary movement<br>Setup time |
| | Low correlation | Rework rate | Unnecessary transportation |
| Visual management systems | High correlation | --- | --- |
| | Medium correlation | Number of work-related injuries | Unnecessary movement |
| | Low correlation | Transportation cost | --- |
| Cellular manufacturing | High correlation | Transportation cost<br>Manufacturing lead time<br>Labour productivity | Unnecessary movement<br>Unnecessary transportation |
| | Medium correlation | Total inventory cost | WIP |
| | Low correlation | Cost per part<br>OEE<br>Rework rate<br>Customer satisfaction | Setup time<br>Defects |
| Single Minutes Exchange of Die | High correlation | Setup time | Setup time |
| | Medium correlation | Manufacturing lead time | --- |
| | Low correlation | --- | --- |
| Safety improvement programs | High correlation | Number of work-related injuries | Failure time |
| | Medium correlation | --- | --- |
| | Low correlation | --- | --- |
| Information management systems | High correlation | Supplier responsiveness | Knowledge disconnection |
| | Medium correlation | On-time delivery | WIP<br>Raw material inventory |
| | Low correlation | Total inventory cost<br>Setup time | --- |

TABLE IV
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 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 5S |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | TPM |
| 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | JIT |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | TQM |
| 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Kanban |
| 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Production smoothing |
| 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | Standard work process |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Visual management |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | Cellular manufacturing |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | SMED |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | Safety improvement system |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Information flow management system |

| 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

TABLE V
STATION 4'S PERFORMANCE METRICS WITH RELATIVE IMPORTANCE WEIGHTINGS

| Performance metrics | Relative importance weightings |
|---|---|
| Cost per part | 9 |
| Total inventory cost | 7 |
| Transportation cost | 8 |
| Setup time | 9 |
| Manufacturing lead time | 6 |
| Labour productivity | 5 |
| OEE | 8 |
| Rework rate | 5 |
| Customer satisfaction | 6 |
| Number of work-related injuries | 4 |
| Supplier responsiveness | 4 |
| On-time delivery | 5 |

TABLE VI
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 |

TABLE VII
LEAN STRATEGIES COST AND TIME UNITS

| Lean tools | Operating cost | Amortization cost | Validation 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 |
| JIT | 8 | 4 | 3 | 7 | 6 | 5 | 8 | 4 |
| Total quality management | 8 | 4 | 4 | 3 | 5 | 4 | 6 | 4 |
| 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 |
| SMED | 6 | 4 | 2 | 5 | 6 | 6 | 4 | 4 |
| Safety improvement program | 7 | 3 | 2 | 2 | 4 | 3 | 4 | 2 |
| Information flow management system | 5 | 9 | 3 | 1 | 9 | 8 | 6 | 4 |

TABLE VIII
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 |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 4 | 4 | 6 | 7 | 5 | 7 | 8 | 7 | 9 | Relative importance weights |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 5S |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | TPM |
| 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | JIT |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | TQM |
| 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Kanban |
| 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Production smoothing |
| 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | Standard work process |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Visual management |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | Cellular manufacturing |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | SMED |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | Safety improvement system |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Information flow management system |

| 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 7 | 8 | 9 | 6 | 5 | 8 | 5 | 6 | 4 | 4 | 5 |
| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

TABLE IX
COMPANY TIME AND BUDGET LIMITATIONS FOR LEAN IMPLEMENTATION

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

TABLE X
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 |

### *B. 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 fluctuation 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 is defined 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 XIII 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 (see Fig. 1).

The maximum value obtained by implementing the best combination of lean tools is 79, and the minimum is 6. The comparison of the new budget and period limitations with actual budget and time required for implementing appropriate lean initiatives is provided in Table XII. 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. 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.

TABLE XI
THE BEST COMBINATION OF LEAN STRATEGIES, PERFORMANCE METRICS AND MANUFACTURING WASTES

| PERCEIVED VALUE | Knowledge disconnection | Raw material inventories | WIP | Failure time | Over processing | Final goods inventory | Unnecessary transportation | defects | Setup time | Unnecessary movements | Manufacturing wastes / Performance metrics |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | 4 | 4 | 6 | 7 | 5 | 7 | 8 | 7 | 9 | Relative importance weights |
| | $W_{10}$ | $W_9$ | $W_8$ | $W_7$ | $W_6$ | $W_5$ | $W_4$ | $W_3$ | $W_2$ | $W_1$ | Selected wastes / Selected metrics |
| 47 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | **5S** |
| 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | TPM |
| 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | **JIT** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | **TQM** |
| 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | **Kanban** |
| 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | **Production smoothing** |
| 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | **Standard work process** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Visual management |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | **Cellular manufacturing** |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | **SMED** |
| 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | Safety improvement system |
| 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Information flow management system |

| 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 | PERCEIVED VALUE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 7 | 8 | 9 | 6 | 5 | 8 | 5 | 6 | 4 | 4 | 5 | |
| $M_1$ | $M_2$ | $M_3$ | $M_4$ | $M_5$ | $M_6$ | $M_7$ | $M_8$ | $M_9$ | $M_{10}$ | $M_{11}$ | $M_{12}$ | |
| 1 | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 47 |
| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |

TABLE XII
ACTUAL COST AND TIME WITH COST AND TIME CONSTRAINTS IN 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 |

TABLE XIII
THE BEST COMBINATIONS OF LEAN STRATEGIES, PERFORMANCE METRICS AND MANUFACTURING WASTES IN DYNAMIC SITUATION

| PERCEIVED VALUE | Knowledge disconnection | Raw material inventories | WIP | Failure time | Over processing | Final goods inventory | Unnecessary transportation | defects | Setup time | Unnecessary movements | Manufacturing wastes / Performance metrics |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | 4 | 4 | 6 | 7 | 5 | 7 | 8 | 7 | 9 | Relative importance weights |
| | $W_{10}$ | $W_9$ | $W_8$ | $W_7$ | $W_6$ | $W_5$ | $W_4$ | $W_3$ | $W_2$ | $W_1$ | Selected wastes / Selected metrics |
| 41 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 5S |
| 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | TPM |
| 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | **JIT** |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | **TQM** |
| 1 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | **Kanban** |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | Production smoothing |
| 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | **Standard work process** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | Visual management |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | **Cellular manufacturing** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | SMED |
| 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | Safety improvement system |
| 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **Information flow management system** |

| 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 | PERCEIVED VALUE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | 7 | 8 | 9 | 6 | 5 | 8 | 5 | 6 | 4 | 4 | 5 | |
| $M_1$ | $M_2$ | $M_3$ | $M_4$ | $M_5$ | $M_6$ | $M_7$ | $M_8$ | $M_9$ | $M_{10}$ | $M_{11}$ | $M_{12}$ | |
| 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 38 |
| 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 |
| 0 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 1 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |

## VIII. 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 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 comparing to the previous methods. The developed methodology suggests more accurate sequence of lean techniques for implementation that not only impact the critical production wastes but also improve identified performance metrics significantly. Therefore, implementation of the suggested lean tools helps manufacturers to perform in the competitive market efficiently while reducing manufacturing wastes. The developed methodology in this research clearly identifies 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 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 both improving performance metrics and reducing manufacturing wastes.
- A multi-objective methodology that suggests more accurate sequence of lean tools for implementation that improves identified performance metrics as well as eliminating production wastes.
- A methodology that illustrates the effect of lean initiatives directly on performance metrics beside manufacturing wastes.

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