A time-based quantitative approach for selecting lean strategies for manufacturing organisations

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Lean strategies have been developed to eliminate or reduce waste and thus improve operational efficiency in a manufacturing environment. However, in practice, manufacturers encounter difficulties to select appropriate lean strategies within their resource constraints and to quantitatively evaluate the perceived value of manufacturing waste reduction. This paper presents a methodology developed to quantitatively evaluate the contribution of lean strategies selected to reduce manufacturing wastes within the manufacturers’ resource (time) constraints. A mathematical model has been developed for evaluating the perceived value of lean strategies to manufacturing waste reduction and a step-by-step methodology is provided for selecting appropriate lean strategies to improve the manufacturing performance within their resource constraints. A computer program is developed in MATLAB for finding the optimum solution. With the help of a case study, the proposed methodology and developed model has been validated. A ‘lean strategy-wastes’ correlation matrix has been proposed to establish the relationship between the manufacturing wastes and lean strategies. Using the correlation matrix and applying the proposed methodology and developed mathematical model, authors came out with optimised perceived value of reduction of a manufacturer’s wastes by implementing appropriate lean strategies within a manufacturer’s resources constraints. Results also demonstrate that the perceived value of reduction of manufacturing wastes can significantly be changed based on policies and product strategy taken by a manufacturer. The proposed methodology can also be used in dynamic situations by changing the input in the programme developed in MATLAB. By identifying appropriate lean strategies for specific manufacturing wastes, a manufacturer can better prioritise implementation efforts and resources to maximise the success of implementing lean strategies in their organisation.

Keywords: lean manufacturing strategies; wastes; lean implementation time; time constraints; mathematical model; optimisation

1. Introduction

In today’s competitive market, manufacturing firms are facing considerable pressure due to customer’s expectation about product quality, demand responsiveness, lower cost and product variety (Nahm et al. 2006, Karim et al. 2008, Islam and Karim 2011). To meet such expectations, the manufacturing industry is focusing on advanced manufacturing strategies in particular the ‘manufacturing-task strategy’ and ‘manufacturing-choice strategy’ (Miller and Roth 1994, Swink and Way 1995). The first strategy concerns the competitive capability the manufacturing firm must accomplish in order to compete successfully in its business or marketing environment (Davies and Kochhar 2002, Leung 2002). On the other hand, the manufacturing-choice strategy represents the appropriate selections of technologies and management strategies to improve the manufacturing system.

Leung (2002) stated that manufacturing performance metrics such as quality, cost/efficiency and flexibility are the first decision area for implementing a manufacturing strategy. The second decision area of the manufacturing strategy is the manufacturing choice strategy. Different areas of industries do not have the same level of strategy implementation and the same strategies to follow. Moreover, it is often not easy to select a proper strategy to address a company’s problems (Wan and Chen 2008). Therefore, the current interest of research about the manufacturing choice strategy is about the prudent adoption of the various best practices or advanced manufacturing techniques.

Lean manufacturing is defined as a multi-dimensional approach that includes a variety of effective manufacturing practices, including just-in-time (JIT), total quality management (TQM), standard work process,
work groups, manufacturing cells, total productive maintenance (TPM) and suppliers’ involvement in an integrated environment. The key driving force of the lean concept is that these practices can work synergistically to create a systematised and high quality system. It also fulfils customer demands at the required pace (Shah and Ward 2003). Pavanskar et al. (2003) and Zakuan and Mat Saman (2009) stated that companies have misapplied lean strategies during the conversion to a lean organisation. These misapplications can be identified as ‘use of a wrong tool to solve a problem, use of a single tool to solve all of the problems and use of all tools (same set of tools) for each problem’ (Marvel and Standridge 2009). Applying lean strategies incorrectly increases inefficiencies of an organisation’s resources and reduced employee confidence in lean strategies (Marvel and Standridge 2009). Therefore, applying the appropriate strategy at the appropriate time for the appropriate company for the right purposes is very important.

The success and implementation of any particular management strategy normally depends upon organisational characteristics, which means that all organisations should not or cannot implement a similar set of strategies in their particular case (Shah and Ward 2003). Consideration of organisational contexts such as organisation size, organisation resource limitations have been noticeably lacking in research on implementation of lean strategies such as JIT and TQM programs or other advanced manufacturing practices (Shah and Ward 2003). As a result, the impact of lean programs on organisational performance has been mixed (Samson and Terziovski 1999, Shah and Ward 2003, 2007).

Many researchers (Womack et al. 1990, Comm and Mathaisel 2000, Lewis 2000, Mejabi 2003, Shah and Ward 2003, 2007, Rivera and Frank Chen 2007, Puvanasvaran et al. 2008, Taj 2008) have investigated the idea of lean manufacturing and its components, and benefits in manufacturing organisations. Several authors have felt the importance of examining the significant factors such as manufacturer budget, allocated time for productivity improvement, organisational size and resistance from upper management which are vital for the successful implementation of any new productivity initiative in an organisation (Achanga et al. 2006). Moreover, a business should have a clear vision and strategy in forecasting a project’s likely costs and duration in order to implement any productivity drive (Holland and Light 1999). Holland and Light (1999) have investigated from their enterprise resource planning (ERP) case studies that about 90% of their implementations are delayed or over budgeted. Poor cost and schedule estimation are identified as reasons for these occurrences. These findings are also supported by Al-Mashari et al. (2003). They found that regardless of the benefits any productivity improvement package provides, it often costs a huge amount of money to acquire and implement these packages and, more awkwardly, they end up disrupting the existing organisational framework. In most cases, changes brought about by new productivity initiative, such as lean manufacturing, may cause disruption in the very process it is meant to improve. This is mainly because manufacturers generally do not know which lean tool is appropriate for what purpose. Therefore, this research has developed a mathematical model and provides a structured methodology to identify appropriate lean strategies to reduce the most critical wastes from the manufacturing process within manufacturers’ time constraints.

This paper is structured as follows. The next section describes the problem statement and then a mathematical model is developed to quantitatively evaluate the perceived contribution of lean strategies to manufacturing wastes. A structured methodology for selecting appropriate lean strategies is presented in the following section. A computer program developed in MATLAB is used to find optimum solution according to manufacturers’ current improvement targets within their allocated time. Then, a case example is presented to demonstrate the application of developed methodology in practical case. Finally, the limitations of this research and conclusions are presented.

2. Problem description and mathematical model development

Lean strategies have been successfully implemented in manufacturing and service organisations. However, there have been many failures of lean implementation due to the confusion about what and how to adopt lean tools in a specific environment (Tiwari et al. 2007). The identification and selection of inappropriate lean strategy for a given situation can sometimes lead to an increase in waste, cost and production time of a manufacturer. Many researchers developed methods to select appropriate lean strategies based on identified wastes in manufacturing processes. For example, Prasad (1995) proposed a method for the selection of JIT tools. In his developed method, the relationships between performance metrics and organisational objectives is captured using a 10-point rating scale. But the information generated from this relationship is not directly used in ranking or prioritising lean tools. Organisational resource constraints such as cost and time are also not considered by Prasad. A method was developed by Hines and Rich (1997) to select the value stream mapping tools. In their method, they mapped the relations between the
improvement tools and wastes (or process problems). However, they do not attempt to directly assign relative importance (weights) to performance metrics, nor they use these weights to prioritise wastes and tools. Although lean manufacturing strategies are becoming popular as techniques for wastes reduction, manufacturers are still not convinced of the required cost and time of its implementation (Achanga et al. 2006). The main concern of most of these industries is that implementing lean manufacturing is costly and time consuming (Achanga et al. 2006, Browning and Heath 2009). Implementation of lean strategies is always done to make the manufacturing process more efficient. However, it often brings one or more undesired situations as listed below (Bachamada 1999, Gautam and Singh 2008, Browning and Heath 2009):

- Need to commit extra implementation cost.
- Need to commit extra lean implementation time.
- Investment in manufacturing and assembly facilities.
- Changed maintenance and increased cost of part management.
- Increased risk to quality.

At present, theoretical principles for determining the appropriate selection of lean strategies is absent (Leung 2002, Mejabi 2003, Achanga et al. 2006, Moore 2007). Existing methods of selecting the appropriate lean strategy relies on the manufacturers’ common sense of judgement rather than any sets of logical justification. With manufacturers seeking advice for their investment in implementing new lean strategies may desire certain theoretical grounds to assure them that their investment decisions are logically sound (Wacker 1998), it is necessary to develop a methodology to select appropriate lean strategies along with manufacturer focus of improvement areas (wastes) within their resource (time) constraints.

Irrespective of how it is perceived, the concept of lean manufacturing has unarguably been discussed extensively in the past decade or so (Achanga et al. 2006). However, few attempts have been made to develop a methodology of selecting the appropriate lean strategies based on its implementation time constraint and identified manufacturing wastes. In order to reduce the manufacturing wastes by implementing lean strategies and minimise the time of implementation, a systematic methodology needs to be developed. Therefore, this research developed a mathematical model to optimise the time of lean implementation and provided a structured methodology to identify appropriate lean strategies to reduce the most critical wastes from the manufacturing process. In this model, time of lean implementation is included in the form of planning time for lean implementation, modification time of exiting process, training time required for personnel to train about the new system, and validation time for the new production process. In addition, the reduction of any wastes is considered as the increase of manufacturer perceived effectiveness value index. Finally, the optimisation technique provides the maximised perceived value of reduction of a manufacturing waste within given time constraints.

### 2.1 Value index of lean implementation

The objective of implementing a new lean technique in a manufacturing process is to reduce waste and increase productivity. When a change in a system does not contribute to one of the objectives, then it is a non-value added attempt. Therefore, these changes should not be pursued further. This research uses the following two factors to accomplish the above objectives.

- Maximise the perceived value of reduction of manufacturing wastes by implementing lean strategies.
- Minimise the time of lean implementation.

Hence, it is necessary to identify the lean strategies that give maximum perceived value to the reduction of manufacturing wastes at a minimum implementation time. It is assumed that a lean tool or strategy is implemented to bring in leanness to the existing process or to reduce manufacturing cost and time.

Consider $L_i$ is the lean strategy to be implemented to reduce the manufacturing inefficiencies and therefore perceived effectiveness value of implementing a lean strategy $L_i$ is $\delta_i$.

According to Gautam and Singh (2008), an increase in perceived effectiveness value index by implementing $n$ lean strategies can be expressed as

$$\sum_{i=1}^{n} L_i \delta_i$$  \hspace{1cm} (1)
If two strategies are interdependent and each strategy influences others then the extra change in perceived contribution can be expressed as

$$\sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \delta_{2ij}$$

In Equations (1) and (2), $L_i$ is a binary representation of lean strategy implementation and is 1 if the $i$th lean strategy is implemented for the reduction of a specific waste and 0 if it is not implemented. Therefore, implementation of the $i$th lean strategy contributes $\delta_i$, towards a manufacturer’s perceived value. Similarly, if $i$th and $j$th strategies are coupled in such a way that implementation of $i$th strategy forces a change in $j$th strategy, then the resulting contribution towards the manufacturing perceived effectiveness value due to $L_j$ is $\delta_{2ij}$.

Therefore, total change in perceived effectiveness value index = perceived effectiveness value without implementing a lean strategy + perceived effectiveness value due to implementing a lean strategy + perceived effectiveness value of forced changes during lean implementation

$$= \delta_0 + \sum_{i=1}^{n} L_i \delta_i + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \delta_{2ij}$$

Bachamada (1999) stated that any new project involves some level of risk and uncertainty and that a lean project may be considered a high risk but also may provide a high return on investment. This research assumes that the forced changes are most often negative due to increased cost, time and quality risk. For example, implementation of lean strategies JIT and TPM do not automatically increase profit of a company because benefit derived from JIT and TPM adoption may be offset by their many direct and indirect costs. Because, the implementation of both JIT and TPM requires extensive training of employees on pull concepts; identification of key performance parameters; new layout based on U-shaped cells; standardisation of operations; a maintenance plan for each machine; housekeeping, visual control and multi-skill training. Considering, JIT and TPM are two interrelated lean strategies, the implementation of these two strategies together therefore requires a balanced relationship during implementation. Implementation of JIT and TPM together without considering the positive and negative impact on each other sometimes may cause negative impact on overall system performance like increased implementation cost or time.

Assume that, the production system implements $n$ number of strategies and each strategy contributes in overall perceived value of the manufacturing environment. Four major types of time elements are considered in order to implement required lean a strategy(s) in the existing system to reduce the identified wastes. These are planning time, modification time, training time and validation time. The next section refers to the time required for each selected strategy to be implemented.

2.2 Projected lean implementation time

Resources are necessary to implement any new tools or techniques in an existing system. Therefore, the effort required to make the transition to lean manufacturing should not be underestimated (Hobbs 2004). Time is considered one of the most important resources to successful lean implementation in this global competitive environment. Because, extra time is required for detailed design, training for personnel, development of support technologies as well as total system maintenance for the implementation of each selected lean manufacturing initiative. Different lean strategies identified from literature are presented in the 1st column of Table 1 and their required implementation times are provided in the 2nd, 3rd, 4th and 5th columns of Table 1. This research calculates estimated time (planning, modification, training and validation) to implement each selected strategy, based on the complexity of manufacturing operations and level of lean (a) strategy/strategies implementation (basic, moderate or comprehensive) in a specific manufacturing process. Development time or lean implementation time shall be within the project duration time and time should be kept at a minimum for the successful implementation of lean for a specific project. This research assigns the amount of time required for each strategy in time units from a maximum time of 10 units as shown in Table 1. Planning, modification, training, and validation time of implementing ‘5S’ are 3 units, 2 units, 2 units, and 2 units respectively based on comprehensive implementation of this strategy, as shown in Table 1.
2.2.1 Planning time index

It is very difficult or sometimes impossible to know exactly about all the activities that need to be carried out in order to implement a new project and how much cost and time are required for a specific project. Implementation of lean techniques or strategies in the existing system requires planning from the top management before implementation. Moreover, several activities are related to put in practice a new improvement strategy such as development of functional requirements, development of technical specifications, facilities development, development of implementation process and procedures etc. Therefore, it needs extra planning time to accomplish a lean project.

If $L_i$ is the lean strategy for reduction of certain manufacturing waste and $T_{P_i}$ is the required planning time for this lean strategy implementation; then the total planning time required for implementing $n$ strategies and upgrading the existing system

$$
\sum_{i=1}^{n} L_i T_{P_i}
$$

If one lean strategy implementation causes forced changes to the others therefore extra planning time is required to take appropriate measure for the forced changes and which can be expressed as;

$$
\sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{P_{ij}}
$$

If $i$th and $j$th strategies are closely linked strategies and, therefore, the implementation of $i$th strategy forces a change in $j$th strategy, this results in an extra amount of planning time denoted by $T_{P_{ij}}$. The extra amount of planning time is the result of the impact of lean strategy $L_j$.

Therefore, total planning time for implementing a lean strategy = planning time required for a production process without lean implementation + time required for implementing a lean strategy + time required for unexpected change due to implementing a lean strategy

$$
T_{P_0} + \sum_{i=1}^{n} L_i T_{P_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{P_{ij}}
$$

where $T_{P_0}$ is the planning time required for a project without implementing any lean strategy.

2.2.2 Modification time index

Modification time can be defined as the amount of time required for the modification of the existing system for implementing the selected lean strategy.

<table>
<thead>
<tr>
<th>Lean Initiatives</th>
<th>Planning time</th>
<th>Modification time</th>
<th>Training time</th>
<th>Validation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>5S</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Total productive maintenance (TPM)</td>
<td>8</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Just-in-time (JIT)</td>
<td>7</td>
<td>8</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Total quality management (TQM)</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Pull/Kanban system</td>
<td>7</td>
<td>5</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Production smoothing</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Standard work process</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Visual management system</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Cellular manufacturing</td>
<td>8</td>
<td>4</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>Single minute exchange of dies (SMED)</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Safety-improvement programs</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Information management system</td>
<td>9</td>
<td>7</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 1. Lean strategies implementation time.
If \( L_i \) is the lean strategy for the improvement of certain manufacturing waste and \( T_{M_{ij}} \) is the required modification time for this lean tool implementation, then the total time required for modification of the existing system due to the implementation of \( n \) strategies is

\[
\sum_{i=1}^{n} L_i T_{M_{ij}}
\] (7)

If one lean strategy implementation causes forced changes to the others then the amount of extra time needed can be expressed as;

\[
\sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{M_{ij}}
\] (8)

If \( i \)th and \( j \)th strategies are closely linked strategies and therefore, the implementation of \( i \)th strategy forces a change in \( j \)th strategy, which results in extra amount of modification time denoted by \( T_{M_{ij}} \). The extra amount of modification time is the result of the impact of lean strategy \( L_j \).

Therefore, total modification time for implementing a lean strategy = modification time required for a production process without lean implementation + modification time required during lean implementation + modification time required for unexpected change during lean implementation

\[
= T_{M_{0i}} + \sum_{i=1}^{n} L_i T_{M_{ij}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{M_{ij}}
\] (9)

where, \( T_{M_{0i}} \) is the modification time required for a project without implementing any lean strategy.

2.2.3 Training time index

Training is an important issue for successful implementation of lean. Replication of lean strategies from others is not a practical way of developing lean manufacturing system. In most cases, copying of lean strategies from others lead to failure and sometimes result in lean that is not applicable to that specific manufacturing process. Therefore, proper knowledge about lean is very important part of successful implementation of lean strategies in any organisation. Employees should be trained in different skills to perform different kinds of tasks in the production process. As, for example, operators who were previously in assembly process are trained in parts manufacturing and vice versa. Employees also trained in performing various indirect tasks such as leadership training in order to be able to alternate the leadership among employees in the team. Therefore, time is required for training personnel about a specific lean strategy, its relation to specific wastes reduction, its implementation process, its maintenance process, and its operation.

Similarly, if \( L_i \) is the lean strategy for the improvement of any particular manufacturing waste and \( T_{T_{ij}} \) is the required training time to teach operators about this particular lean tool; then the relationship of training time and the implemented lean tool can be expressed as;

\[
\sum_{i=1}^{n} L_i T_{T_{ij}}
\] (10)

If one lean strategy implementation causes forced changes to the other tools or a part of the existing manufacturing process then an extra amount of time is needed to train up operators to fix the unexpected situation which can be expressed as;

\[
\sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{T_{ij}}
\] (11)

When \( i \)th and \( j \)th strategies are coupled together in such a way that implementation of \( i \)th strategy forces a change in \( j \)th strategy and these forced changes result in extra training time \( T_{T_{ij}} \). Extra training time is the impact of lean strategy \( L_j \).
Therefore, total training time for implementing a lean initiative = Training time required without implementing a
lean strategy + Training time required for lean implementation + training time required for handling unexpected
situation during lean implementation

\[ T_{T_0} + \sum_{i=1}^{n} L_i T_{T_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{T_{ij}} \]  

(12)

where, \( T_{T_0} \) is the training time required for a project without implementing any lean strategy.

2.2.4 Validation time index
After implementing any lean strategy, a process needs to be validated before going to final implementation
(Standridge and Marvel, 2006). Validation is required in order to reduce the risk of increased waste and reduce cost.
It is also required to provide evidence that equipment, item or system have a direct, indirect or no impact on the
product quality due to changes in the existing system after lean implementation. Moreover, validation proves that
systems are validated to confirm effectiveness and to comply with regulatory requirements. Therefore, it needs extra
time to validate the process after lean implementation which effects the total production lead time (Standridge and
Marvel, 2006, Miller et al. 2010).

Validation time can be expressed similar to modification and training time. Therefore, the total validation time
can be expressed as;

\[ T_{V_0} + \sum_{i=1}^{n} L_i T_{V_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{V_{ij}} \]  

(13)

where \( T_{V_0} \) is the validation time required for a production process without lean implementation; \( T_{V_i} \) the extra
validation time required after lean implementation; and \( T_{V_{ij}} \) the extra validation time required for handling
unexpected situation during lean implementation.

2.2.5 Decision function
The objective of this study is to maximise the manufacturer perceived value of the reduction of identified
manufacturing wastes by implementing lean strategies within their limited time. Mathematically, it can be
expressed as

\[ \text{Max} = \delta_0 + \sum_{i=1}^{n} L_i \delta_{1i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \delta_{2ij} \]  

(14)

and

\[ \text{Min} = f \left( \left( T_{P_0} + \sum_{i=1}^{n} L_i T_{P_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{P_{ij}} \right), \left( T_{M_0} + \sum_{i=1}^{n} L_i T_{M_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{M_{ij}} \right), \left( T_{T_0} + \sum_{i=1}^{n} L_i T_{T_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{T_{ij}} \right), \left( T_{V_0} + \sum_{i=1}^{n} L_i T_{V_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{V_{ij}} \right) \right) \]  

(15)

Therefore, change in perceived value of reduction of a waste per unit time can be expressed as

\[ \frac{\delta_0 + \sum_{i=1}^{n} L_i \delta_{1i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j \delta_{2ij}}{f \left( \left( T_{P_0} + \sum_{i=1}^{n} L_i T_{P_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{P_{ij}} \right), \left( T_{M_0} + \sum_{i=1}^{n} L_i T_{M_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{M_{ij}} \right), \left( T_{T_0} + \sum_{i=1}^{n} L_i T_{T_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{T_{ij}} \right), \left( T_{V_0} + \sum_{i=1}^{n} L_i T_{V_i} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{V_{ij}} \right) \right) \} \]  

(16)

In the above equation, \( f \) is the function of time index to perceived effectivenes value index. The objective in this
analysis is to maximise the perceived value of reduction of a manufacturing waste within the limited time.
2.2.6 Constraints

No manufacturing organisation has unlimited resources and time for implementing a new technique. Therefore, any new development programme has some targets and resource constraints. Several major time-based constraints are considered in this analysis:

Planning time ($PT_C$):

\[
\left( \sum_{i=1}^{n} L_i T_{P_{i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{P_{ij}} \right) \leq \text{Allocated planning time} \tag{17}
\]

Modification time ($MT_C$):

\[
\left( \sum_{i=1}^{n} L_i T_{M_{i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{M_{ij}} \right) \leq \text{Allocated modification time} \tag{18}
\]

Training time ($TT_C$):

\[
\left( \sum_{i=1}^{n} L_i T_{T_{i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{T_{ij}} \right) \leq \text{Allocated training time} \tag{19}
\]

Validation time ($VT_C$):

\[
\left( \sum_{i=1}^{n} L_i T_{V_{i}} + \sum_{i=1}^{n} \sum_{j=1}^{n} L_i L_j T_{V_{ij}} \right) \leq \text{Allocated validation time} \tag{20}
\]

Total Lean Implementation time $\leq$ Total allocated time \tag{21}

3. Methodology for finding optimum solution

In this research, a systematic methodology has been developed to make optimum decisions for improving the identified wastes by implementing appropriate lean strategies within a manufacturer’s time constraints. In this section, a developed methodology has been described for identifying most critical wastes along with appropriate lean strategies with the help of mathematical models developed in the previous section. A schematic chart of the process flow is depicted in Figure 1.

A detail of the developed methodology is described in the following sections.

3.1 Identify the wastes in a manufacturing system and determine manufacturer’s relative importance value

Manufacturing process activities are classified into three categories, namely: value-added activities (VA), non-value-added activities (NVA), necessary but non-value-added activities (NNVA) (Hines and Rich 1997). VA activity ‘directly results in the addition of value in the eyes of the end customer so that this kind of activity is considered essential with regard to the perceived quality of final offering and regulatory compliance’. NVA is ‘any activity which adds cost but creates no value so it should be removed immediately’. NVA is a kind of pure waste which needs to be eliminated immediately. It is notable that this kind of activity needs to be reduced or eliminated with ‘minimum or no capital investment and with no detrimental impact on end value’ in a short run. NNVA is an activity which creates no value but is still necessary because of the current limitation of technology, capital assets and ‘operating procedures of the system under examination’. The most commonly recognised manufacturing wastes included in this methodology are defects, unnecessary transportation, unnecessary motion, setup time, finished goods inventory, inappropriate processing, failure time, work-in-process (WIP), raw material inventory, and lack of integrated approach (Hines and Rich 1997, Karim et al. 2010). Then relative importance will be given to each waste according to the manufacturer’s current situation.
Various lean strategies have been developed to reduce the non-value adding activities and enhance leanness of manufacturing systems (Wan and Chen 2008). However, the selection of lean strategies should be in such a way that implementing lean strategies should not increase other non-value adding activities in the manufacturing process. Therefore, appropriate lean strategies must be selected to eliminate wastes or improve the performance in the manufacturing process within their limited implementation time. Moreover, it would be preferable to select the lean strategies that have the most impact overall on the identified wastes or performances, according to manufacturers’ priority. As a result, different companies implement different strategies to become lean (Bayou and de Korvin 2008).
In this study, important lean strategies along with their impact on different manufacturing wastes are identified from an extensive literature review (Panizzolo 1998, Mejabi 2003, Shah and Ward 2003, Doolen and Hacker 2005, Herron and Braiden 2006, Abdulmalek and Rajgopal 2007, Moore 2007, Shah and Ward 2007, Bayou and de Korvin 2008). The most commonly used lean tools adopted in this paper are total quality management (TQM), single minute exchange of dies (SMED), total productive maintenance (TPM), production smoothing, just in time (JIT), 5S, Kanban, standard work process, visual control, safety improvement programme, cellular manufacturing, and information management system. Incorrect application of lean strategies results in a waste of an organisation's time and resources as well as reduced confidence by employees in lean techniques (Marvel and Standridge 2009). As a result, applying the appropriate tool/s at the right time within the budget for the right type of company is very important. Therefore, several lean techniques may need to be implemented in order to reduce a particular waste. Hence, it is necessary to establish a proper relationship between the closely related lean strategies and manufacturing wastes.

3.3 Establish relationship between lean strategies and manufacturing wastes

In this research, a correlation matrix has been developed between the selected lean strategies and identified manufacturing wastes and provided in Table 2. This correlation matrix is used as initial decision support methodology in this research. A general house of quality method is used for mapping the observed relationships between the lean strategies and wastes. Three levels of correlations have been defined, such as high correlation (rank 3), medium correlation (rank 2), and low correlation (rank 1). In the correlation matrix, the lean strategies which have almost always an impact on a particular waste were ranked 3. Strategies which often and sometimes have an impact on a particular waste were ranked 2 and ranked 1 respectively. Tools with very low, zero or potentially negative direct impact on wastes are not mapped, i.e. the implied mapping is rank 0. The ranking was assigned based on literature review. However, further empirical and analytical validation may be needed to justify this part of the tool selection methodology. In addition, the mappings may potentially vary by industry type.

As indicated in Table 2, the relationship between the lean strategies and selected wastes (setup time reduction) is described by an example. All other relationships are not described due to the space limitations. Setup time waste is
the amount of time wasted to start a manufacturing process to produce a product. It includes time for processing like loading the raw materials, waiting for the raw materials, waiting time due to unavailability of the machines (Hines and Rich 1997). Total productive maintenance (TPM) is considered as an initiative for optimising the reliability and effectiveness of manufacturing equipment (Smith and Hawkins 2004). According to Smith and Hawkins (2004), TPM improves the productivity, equipment availability, quality, and safety through the regular maintenance of manufacturing systems. Therefore, TPM reduces the failure time and cleaning time of a manufacturing process thus TPM may have a little effect on the setup time wastage. Therefore, TPM has low correlation with setup time (rank 1). 5S principles are used to organise a production process so that the tools required during starting of a machine will be in order and easier to find. As a result, 5S usually has a correlation with setup time reduction (rank 2). Single minute exchange of dies (SMED) is a lean strategy that analyses the setup activities and helps to redesign the process steps, products, tooling and equipment, to eliminate or minimise part waiting time associated with setups. If a number of varieties of products are manufactured in a single production line, setup time waste is occurred due to the loading of the raw materials. The main objective of SMED is reducing the changeover time. Therefore, SMED is assigned rank 3 for changeover time or setup time reduction. The variability in the manufacturing process is reduced by a lean strategy, i.e. standard work process. Standard process can often reduce the time to start a process to manufacture a product. Therefore, standard work process is assigned rank 2 with respect to setup time reduction. The number of setups in a manufacturing process sometimes can be reduced by implementing cellular manufacturing (Heragu 1994). This is how cellular manufacturing is assigned rank 1 with respect to setup time reduction.

In our research, to select more appropriate lean strategies according to identified wastes, the previous mapping is redefined and simplified. In this case, a ‘lean strategies – wastes’ correlation matrix has been redeveloped for identifying the most appropriate lean strategies that are closely related to the manufacturing wastes and presented in Table 3. In the simplified case, it is assumed that the maximum impact of a lean strategy on an identified waste is ranked as 1 and otherwise lean strategy on that waste is ranked as 0. Each row of this matrix represents a lean strategy \( L_i \) and each column of this matrix represents a manufacturer’s wastes \( W_j \). In the developed matrix, each lean strategy makes a certain quantifiable contribution towards the improvement of different wastes. It is assumed that if a waste is selected for improvement; value is 1 otherwise 0. Therefore, a value of ‘1’ in the matrix indicates a high contribution of implementation of a lean strategy \( L_i \) for improvement of waste \( W_j \). A value of ‘0’ indicates no or little contribution of implementation of a strategy \( L_i \) for improvement of waste \( W_j \). Table 3 shows the proposed relationships among the lean strategies, manufacturing wastes and the relative importance value of wastes. This proposed matrix will help manufacturers to select the right combination of tools for the right type of problem.

### 3.4 Calculate perceived effectiveness value index of reduction of a manufacturing wastes

As stated above, 10 types of wastes were identified in a manufacturing system. It is very difficult to predict exactly how much the manufacturing waste will be reduced due to implementation of a lean strategy. In Table 3 (2nd row), the relative importance of each waste will be provided according to manufacturer needs. In this step, total perceived effectiveness value of reduction of a manufacturing waste by implementing a lean strategy is calculated by using Equation (1). In this study, if any waste of a manufacturer is mapped to more than one lean initiative, then they share the overall level of perceived effectiveness value. For example, in Table 3, ‘unneeded motion’ has been identified as a critical waste to be minimised by implementing (a) lean strategy/strategies. It is depicted that the improvement of the perceived value of ‘unneeded motion’ comes from the implementing of several lean strategies such as 5S, visual management system, cellular manufacturing, etc. Mathematically, if \( k \)th waste is mapped to \( i \)th and \( j \)th lean initiatives then perceived value change associated with \( k \)th requirement comes from both of these lean strategies, hence it can be expressed as

\[
\nabla_k = \sum_{i=1}^{n} L_{ik} \delta_{1i} + \sum_{j=1}^{n} L_{kj} \delta_{2ij}
\]

\[\text{(22)}\]
Table 3. Lean strategies relative impact on performance metrics.

<table>
<thead>
<tr>
<th>Participating lean strategies</th>
<th>Decision function</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Setup time/Changeover time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unneeded motion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Defects or scrape</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unnecessary transportation</td>
<td></td>
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<tr>
<td></td>
<td>Finished goods inventory</td>
<td></td>
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<tr>
<td></td>
<td>Inappropriate processing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Failure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Work in process (WIP)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Raw material inventory</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knowledge disconnection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unnecessary transportation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Finished goods inventory</td>
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<td></td>
<td>Inappropriate processing</td>
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<td></td>
<td>Failure time</td>
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<tr>
<td></td>
<td>Work in process</td>
<td></td>
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<tr>
<td></td>
<td>Raw material inventory</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Knowledge disconnection</td>
<td></td>
</tr>
</tbody>
</table>

Relative importance by manufacturer $\rightarrow$

Implement lean initiatives if $W_n$ is selected $\rightarrow$

Waste selected for improvement if 1, 0 if not selected

<table>
<thead>
<tr>
<th>$W_1$</th>
<th>$W_2$</th>
<th>$W_3$</th>
<th>$W_4$</th>
<th>$W_5$</th>
<th>$W_6$</th>
<th>$W_7$</th>
<th>$W_8$</th>
<th>$W_9$</th>
<th>$W_{10}$</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>1</td>
<td>1</td>
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<td>1</td>
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<td>1</td>
</tr>
<tr>
<td>$L_1$</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tr>
<tr>
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<td>0</td>
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<td>0</td>
<td>1</td>
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<tr>
<td>$L_5$</td>
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<td>0</td>
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<tr>
<td>$L_9$</td>
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<tr>
<td>$L_{10}$</td>
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<td>0</td>
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<td>1</td>
</tr>
</tbody>
</table>

International Journal of Production Research
3.5 Calculating implementation time of each lean strategy

As mentioned earlier, four types of time are considered for the implementation of a lean strategy: planning time, modification time, training time, and validation time. The value of time is assigned in the form of time units which are representative of relative complexity of lean implementation in an organisation, level of implementation, time required to implementation. In this study, times are calculated based on their level of implementation such as basic, moderate and comprehensive and considered in the form of time units as presented in Table 1. Implementation of a lean strategy in basic level can be described as the strategies are easy to initially design and adapt with the existing manufacturing system and require less or sometimes no planning time or modification time or training time or validation time. Moderate implementation level of lean strategy can be defined as the strategies which require a moderate level of effort to change the existing system. Moderate implementation level also needs medium level of planning, modification, training, and validation time for the new process. Comprehensive implementation means that these strategies are neither easy to initially design nor easy to adapt in the existing system. It requires a high level of planning time, modification time, training time and validation time. In this step, total planning time, modification time, training time and validation time of each lean strategy are calculated using Equations (4), (7), (10) and (13) respectively. In this study it is assumed that if a lean initiative contributes to reduction of a manufacturing waste, its implementation time stays the same even though this lean initiative has influence on the reduction of several wastes. As, for example, in Table 2 it is identified that a lean strategy ‘5S’ is selected for reduction of a manufacturing wastes ‘unneeded motion’. Therefore, they planned for implementing ‘5S’ to improve the ‘unneeded motion’ and determine the time involved with the implementation of ‘5S’. But from Table 2, it can also be seen that ‘5S’ has influence not only on the ‘unneeded motion’ but also on ‘setup time’ and ‘failure time’. We assume that the improvement of others wastes do not add extra implementation time. Therefore, a set of logical constraints are introduced to support this assumption: for each lean strategy $i$,

\[
\begin{align*}
\text{If } \sum (L_{ij}) & \geq 1, \text{ then } T_{P_i} = \text{(Plan-Time-Index)}_i, \text{ Else } T_{P_i} = 0; \\
\end{align*}
\]

(23)

The same sets of constraints are introduced for all time components.

3.6 Finding optimum solution

A program has been developed in MATLAB to solve the equations developed to achieve optimum solution. The developed MATLAB program helps to find appropriate lean strategies for identified wastes within the manufacturer resources constraints using the developed methodology and mathematical model.

The steps required for finding a solution by using the MATLAB program is described below.

- Provide input value as ‘1’ if a requirement (wastes) is selected for improvement of a specific organisation, otherwise put ‘0’ in the developed ‘lean strategy-wastes’ correlation matrix.
- Provide relative importance value of each waste as input according to the manufacturer’s given relative importance.
- Select manufacturer constraints for planning, modification, training, and validation time for the improvement of the most critical wastes. Only lean implementation time is considered in this analysis (i.e. $T_{M_0} = T_{T_0} =$ valid, $T_{P_0} = T_{V_0} = 0$)
- Solve the optimisation problem by running the programme.

This algorithm is applied in the following section to select the critical wastes along with suitable lean strategies based on their resources constraints.

4. Demonstration of developed methodology by a case example

This developed methodology has been demonstrated by a simple case example in order to provide a guideline of how the developed procedure works.
4.1 Case study description

The case organisation, PPL\(^1\), manufacture low and medium voltage switchgear products. The company has a medium voltage switchgear division specialising in medium voltage auto re-closers for both pole mounted and substation applications from 10 kV to 27 kV. These products are offered in voltage ranges from 415 V up to 1000 V, current ratings are up to 4000 A continuous current and 100 kA fault current withstand capacity. The design meets the demanding requirements of the mining and process control industries.

In order to stay competitive the company is keen to embrace lean manufacturing strategy to improve productivity and quality. The problem is how to select appropriate lean strategies appropriate to address their wastes from the huge number of lean strategies within their allocated time constraints. The purpose is to reduce non-value-added activities by implementing appropriate lean strategies. In this section, the developed mathematical model and proposed methodology have been utilised to achieve the above objectives.

4.1.1 Step 1: Identify manufacturing wastes and define manufacturer’s perceived value

Currently, PPL has four main manufacturing lines which are electrical control and communication cubicle assembly line, OSM automatic circuit re-closers assembly line, cable making line and switchgear assembly line. Although research has been carried out in all four manufacturing lines, this paper mainly focuses on electrical control and communication cubicle assembly. Value stream mapping (VSM) is a lean manufacturing technical methodology that helps to interpret the flow of materials and information currently needed to transfer goods or services to the end consumer. In this case study, VSM and time study are used to help the manager to understand entire work processes, identify wastes, highlight problems and imply appropriate solutions. Steps associated with time study are described:

- **Process recording:** At the beginning the operators’ work process are video recorded.
- **Break down and recording step time:** The project team reviews the recorded video and breaks it into time segments that represent each of the details of work process.
- **Categorise the process:** After the time recording, the project team discusses the work process with the manufacturing manager and relevant operator to determine whether the process was value added or non-value added category.
- **Sketch non-value added and value added time spread:** After estimating the time segments an excel spread sheet is used to generate a bar chart to identify the total processing time.

**Identified wastes in the current process:** From the VSM and time study results, the following main problems during assembly process have been identified:

- **Walk distance:** Operators need to walk to get assembly parts and tools all the time; some of the walking times can be treated as non-value added and are considered waste.
- **Handling:** Some double handling problems have been identified, which were mainly caused by lack of operators’ experience.
- **Part replenishment:** Most of the assembled parts are loaded on the work bench. However, there was a miscommunication between operator and the person responsible for replenishment.
- **Waiting and sharing tools:** Currently operators are sharing one set of tools, which may cause increasing waiting time and can be treated as waste.
- **Quality:** Re-working of poor quality parts
- **Layout design:** Inefficient workstation layout and unnecessary distance travelled by operator.

An observation and interview process on the factory floor was conducted to explore further information of the wastes associated with the process. Observation has taken place across the manufacturing process with emphasis on the RC cubicle assembly process. The data obtained from the observation activities were supported by the interview process, which involved most of the workers across the production line and store operators. During the interview, a range of questions were asked, extracting as much information as possible to help the progress of the ongoing project. Finally, current manufacturing problems are categorised under the name of major 10 types of wastes selected in this methodology. Then, relative importance is given to the identified wastes by the project team based on their experience and/or discussing with relevant people (including company executives) and presented in Table 4.
4.1.2 Step 2: Establish relationship between PPL wastes and lean strategies and PPL’s perceived value to reduction of each waste

Planning to reduce manufacturing wastes involves implementation of one or more lean manufacturing initiatives with the objective that each lean manufacturing initiative implemented will contribute to reduce one of the identified wastes. In this step, a complete decisional correlation matrix is developed to show the relationship among the lean strategies, manufacturing wastes and the level of importance of reduction of that specific waste for PPL. The complete decisional matrix is provided in Table 5.

4.1.3 Step 3: Calculate implementation time required for lean strategy

The actual time components for the implementation of each lean strategy are given in Table 1. In this analysis, time required for implementing each lean strategy are determined by company executives and/or lean experts based on their experience. These times are assigned in the form of time units out of maximum 10 units. Therefore, planning time, modification time, training time, and validation time of implementing ‘5S’ in the case organisation are 4 units, 2 units, 2 units, and 2 units respectively as provided in Table 1. These times are representative of relative complexity in existing system, level of implementation, and time required for lean implementation. For example, implementation time of ‘5S’ is described below. Calculation is done based on data provided in Table 5.

Example: Calculation of implementation cost of ‘5S’ ($L_1$)

According to the Equation 18,

$$\sum (L_i) = 1$$

Therefore, from Table 1, Planning time = Planning time index = 4 units, Modification time = Modification time index = 2 units.

Similarly, Training time = Training time index = 2 units, Validation time = Validation time index = 2 units. Though ‘5S’ has influence on the reduction of other wastes; it does not require extra time to improve the other wastes. The total planning time, modification time, training time and validation time for a lean strategy are calculated by using Equation (4), (7), (10) and (13) respectively and the developed MATLAB program. Manufacturer allocated time for improving their inefficiencies at the beginning of the improvement program are used as time constraints which is provided in Table 6. The total planning time, modification time, training time and validation time of a lean strategy are compared to the time constraints provided in Table 6. Finally, the developed MATLAB program is used to find the optimum solution.
Table 5. Decisional correlation matrix.

<table>
<thead>
<tr>
<th>Relevant lean strategies</th>
<th>Decision function</th>
<th>Setup time/Changeover time</th>
<th>Defects or scrape</th>
<th>Unnecessary transportation</th>
<th>Finished goods inventory</th>
<th>Inappropriate processing</th>
<th>Failure time</th>
<th>Work in process (WIP)</th>
<th>Raw material inventory</th>
<th>Knowledge disconnection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative importance by manufacturer $\rightarrow$</td>
<td></td>
<td>$W_1$</td>
<td>$W_2$</td>
<td>$W_3$</td>
<td>$W_4$</td>
<td>$W_5$</td>
<td>$W_6$</td>
<td>$W_7$</td>
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<td>$W_9$</td>
</tr>
<tr>
<td>Implement lean initiatives if $W_n$ is selected $\rightarrow$</td>
<td></td>
<td>$L_1$</td>
<td>$L_2$</td>
<td>$L_3$</td>
<td>$L_4$</td>
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<td>Implement lean initiatives if $W_n$ is selected $\rightarrow$</td>
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<td>Implement lean initiatives if $W_n$ is selected $\rightarrow$</td>
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<td>Implement lean initiatives if $W_n$ is selected $\rightarrow$</td>
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<td>Implement lean initiatives if $W_n$ is selected $\rightarrow$</td>
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<td>$L_7$</td>
<td>$L_8$</td>
<td>$L_9$</td>
</tr>
</tbody>
</table>
4.1.4 **Step 4: Finding a solution using a model**

The model is solved for optimising the perceived value of reduction of manufacturing wastes. Solution procedure provided in the previous section in Step 5 is used for finding optimum solution. Total time calculated in the previous step and time constraints given by a manufacturer are used to solve the optimisation problem. Manufacturer allocated time for improving their inefficiencies (Table 6) are used as time constraints. Finally, the developed MATLAB program generated optimum solution for the case organisation applying Equation (16). The optimised results are provided in Table 7. Case study results showed that the case organisation can improve unneeded motion, setup time, defects, unnecessary transportation, inappropriate processing and failure time within their given time. Therefore, they can implement 5S, TPM, TQM, standard work process, visual management system, cellular manufacturing, SMED and safety improvement programme. The total perceived value of reduction of selected wastes is calculated as 45 and optimum for this specific case organisation within their time constraints (Table 7).

4.1.5 **Step 5: Implementation and evaluation**

The lean strategies selected for the manufacturing process in the previous step are put in practice and evaluated for a period of time sufficient to see the effectiveness of the strategies. Once the improvement procedure works, a new iteration should be performed in order to continuously set new improvement targets. Manufacturing performance metrics that can be used to evaluate the lean manufacturing process are: Process throughput, line efficiency, total manufacturing lead time, processing time ratio, material handling time ratio, setup time ratio, equipment and personnel waiting time ratio, materials waiting time ratio, information waiting time ratio, scrap rate, rework rate, cost per part, inventory level, inventory cost, labour productivity and capital productivity.

5. **Result analysis**

A computer code of objective function is developed in MATLAB platform. The objective of this program is to maximise the perceived effectiveness value of reduction of identified manufacturing wastes by selecting appropriate lean strategies within the manufacturer time constraints. The MATLAB program generates 476 different combinations of selected wastes and their associated lean strategies within the time constraints by using optimisation Equation (16). This means that a manufacturer can choose 476 different combinations of their identified 10 wastes and combination of lean strategies to address these wastes within their time constraints. From this analysis, manufacturer can easily identify their appropriate options regarding lean strategy selection for their organisation within their time constraint. The result also shows that the minimum and maximum perceived effectiveness value of reduction of identified wastes can be achieved by company PPL within their given time is 4 and 45 respectively. This result also demonstrates that out of 10 wastes identified, PPL can potentially minimise at least one waste and maximum six wastes within their resource limitation. This selection is purely based on minimising and maximising the manufacturer perceived effectiveness value, while satisfying the given set of time constraints. Different time units used as constraints are given by the manufacturers and the actual amount of time for implementing these selected lean strategies in order to improve the selected wastes are acquired from the developed methodology provided in Figure 1 and presented in Table 8.

5.1 **Application of the methodology in a dynamic situation**

Manufacturing organisations run in a dynamic environment and consequently deal with performance measurement as a dynamic process (Suwignjo et al. 2000), therefore it is understandable that the performance measures may change over time and vary between companies. As a result, wastes that are critical today could change and become less harmful after a period of time. Moreover, manufacturers can change their allocated time for improvement...
Table 7. Solution with a given set of constraints.

<table>
<thead>
<tr>
<th>Decision function</th>
<th>Table 7. Solution with a given set of constraints.</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>Unneeded motion</td>
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<td>Relative importance by manufacturer →</td>
<td>L₁</td>
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<tr>
<td>Implement lean initiatives if ( W_n ) is selected →</td>
<td>( W_1 )</td>
</tr>
<tr>
<td>Waste selected for improvement if 1, 0 if not selected</td>
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</tr>
<tr>
<td>5S</td>
<td>L₂</td>
</tr>
<tr>
<td>Total productive maintenance (TPM)</td>
<td>L₃</td>
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<tr>
<td>Just-in-time (JIT)</td>
<td>L₄</td>
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<tr>
<td>Total quality management (TQM)</td>
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</tr>
<tr>
<td>Pull/Kanban system</td>
<td>L₆</td>
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<tr>
<td>Production smoothing</td>
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<tr>
<td>Standard work process</td>
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<td>Visual management system</td>
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<td>Single minute exchange of dies (SMED)</td>
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</tr>
<tr>
<td>Information management system</td>
<td>L_{13}</td>
</tr>
<tr>
<td>Number of lean strategies participating in the improvement process</td>
<td>L_{14}</td>
</tr>
</tbody>
</table>

International Journal of Production Research
project according to their production requirements. The changes could be the result of internal performance improvement strategies or because of changes in the external environment of the company. The developed methodology is capable of dealing with these dynamic situations (see solution procedure). For dynamic decision making by using the developed MATLAB program, the manufacturer needs to change the input, i.e. which wastes they need to improve and their relative importance value. Therefore, it is important to recognise the changes in relative importance value of manufacturing wastes and manufacturing constraints quickly so that the quantitative basis of the developed model is redesigned to reflect the true picture.

Once a waste is selected in the solution, it brings a set of tools that are required to improve that waste. This is also accomplished by introducing a set of constraints.

\[ \text{For all } L_{ij}, \{\text{Dynamic value of } L_{ij} = \text{Static value } L_{ij} \times W_j\} \] (24)

As, for example, ‘unneeded motion’ may be currently considered as the most critical waste for PPL but it can be changed at any time based on the company’s changed situation. In the changed situation, PPL may find other waste such as ‘setup time’ as the critical waste. Therefore, the company needs to change their relative importance for ‘setup time’ which will result in different combination of lean strategies and perceived values within the given new time constraints. In the new case, setup time is considered as the most critical waste (relative importance 9). By using Equation (24), the developed MATLAB program solved the optimisation problem and gives a set of manufacturing wastes that can be improved by implementing appropriate lean strategies within the resources constraints in the solution matrix and presented in Table 9. The 1st iteration with initial time constraint and the actual time required for implementing selected lean strategies are provided in Table 10 (Columns 2 and 3). Then, the new (readjusted) time constraints are set according to the previous solution and the new solution is achieved using the MATLAB program and presented in Table 10 (Columns 4 and 5).

6. Conclusions

Identification of manufacturing improvement areas and selection of the proper tool to overcome these are always a significant challenge in manufacturing organisations. It is important to optimise the benefits of lean implementation within the given set of budgetary constraints and allocated implementation time. This research developed a mathematical model and a systematic methodology to estimate the manufacturer perceived effectiveness value of reduction of manufacturing wastes by implementing appropriate lean strategies within the allocated improvement time given by a manufacture. This developed methodology provided a way to select appropriate lean strategies so that selected lean strategies can help to achieve maximum benefit by minimising the most critical wastes. With the help of a mathematical model, this paper presented the concepts and systematic methodology for optimising the benefits of the lean implementation in terms of the manufacturer perceived effectiveness value within the given set of constraints. In all practical cases, it is important to identify the most critical wastes and selection of proper lean strategy to minimise these wastes within the limitations. With the help of a case example, a step-by-step method is demonstrated to support decision making for choosing the most critical wastes while maximising the perceived effectiveness value. This research also provided the methods to take decisions on special situations such as focusing on the dynamics of a manufacturing system.

Future research must investigate the interdependency of the lean strategies and the impact of the interdependency on the identified wastes. This methodology can be extended to take special decisions on resource reallocation in future research. The future research also evaluates the impact of selected lean tools on the related

<table>
<thead>
<tr>
<th>Table 8. Initial time constraints and actual time required to implementation.</th>
<th>Initial constraint</th>
<th>Time with initial solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning time</td>
<td>45 units</td>
<td>44 units</td>
</tr>
<tr>
<td>Modification time</td>
<td>55 units</td>
<td>39 units</td>
</tr>
<tr>
<td>Training time</td>
<td>35 units</td>
<td>34 units</td>
</tr>
<tr>
<td>Validation time</td>
<td>35 units</td>
<td>29 units</td>
</tr>
</tbody>
</table>

M.A. Amin and M.A. Karim
Table 9. Solution with a new set of combination and time constraints.

<table>
<thead>
<tr>
<th>Change in manufacturer perceived value = 38</th>
<th>Decision function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unneeded motion</td>
<td>Setup time/Changeover time</td>
</tr>
<tr>
<td>Relative importance by manufacturer →</td>
<td>8</td>
</tr>
<tr>
<td>Implement lean initiatives if $W_n$ is selected →</td>
<td>$W_1$</td>
</tr>
<tr>
<td>Waste selected for improvement if 1, 0 if not selected</td>
<td>1</td>
</tr>
<tr>
<td>SS</td>
<td>$L_1$</td>
</tr>
<tr>
<td>Total productive maintenance (TPM)</td>
<td>$L_2$</td>
</tr>
<tr>
<td>Just-in-time (JIT)</td>
<td>$L_3$</td>
</tr>
<tr>
<td>Total quality management (TQM)</td>
<td>$L_4$</td>
</tr>
<tr>
<td>Pull/Kanban system</td>
<td>$L_5$</td>
</tr>
<tr>
<td>Production smoothing</td>
<td>$L_6$</td>
</tr>
<tr>
<td>Standard work process</td>
<td>$L_7$</td>
</tr>
<tr>
<td>Visual management system</td>
<td>$L_8$</td>
</tr>
<tr>
<td>Cellular manufacturing</td>
<td>$L_9$</td>
</tr>
<tr>
<td>Single minute exchange of dies (SMED)</td>
<td>$L_{10}$</td>
</tr>
<tr>
<td>Safety-improvement programmes</td>
<td>$L_{11}$</td>
</tr>
<tr>
<td>Information management system</td>
<td>$L_{12}$</td>
</tr>
<tr>
<td>Number of lean strategies participating in the desired process</td>
<td>3</td>
</tr>
</tbody>
</table>
performance metrics. It is expected that concepts generated from this research would make a significant contribution to the selection of appropriate lean tools in a manufacturing organisation.

Note

1. For reasons of confidentiality, the name of the manufacturer cannot be disclosed. PPL is a pseudonym.

References


