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Framework for Lean Implementation Through Fuzzy AHP-COPRAS Integrated Approach

Manickam Bhuvanesh Kumar ©, Rathinasamy Parameshwaran ©, Jiju Antony ©, and Elizabeth Cudney ©

Abstract—Manufacturing industries strive hard to improve their productivity to meet the highly demanding business market. Productivity can be improved by effective use of resources, elimination of wastes, process flow enhancement, and continuous improvement. There are strategies and tools to improve productivity but industries face the problem of selecting appropriate strategies. Lean manufacturing philosophy helps the manufacturing industries to enhance their productivity aspects by identifying and eliminating the wastes using specific tools/techniques. This article presents an integrated framework for the lean implementation process in the steel processing industry. The value stream mapping (VSM) tool is used to identify the wastes at each stage of the production process. Lean tools are identified from literature based on the wastes identified from the current state. For prioritizing the lean tools based on the positive correlation on one another, fuzzy integrated analytic hierarchy process and complex proportional assessment of alternatives are used. A future state value stream map is developed to illustrate the improvements achieved due to the implementation of selected lean tools. Comparison of present and future state VSM shows a great reduction of wastes, such as scale waste (50%), miss roll defects (72.7%), size variation defect (62%), corrosion defect, and improvements in talk time and cleanliness.

Index Terms—Fuzzy analytic hierarchy process (AHP), fuzzy complex proportional assessment of alternatives (FCOPRAS), lean manufacturing (LM), steel processing industry, value stream mapping (VSM), waste reduction.

I. INTRODUCTION

GLOBAL competition has forced many manufacturing industries to incorporate new productivity improvement strategies. The lean manufacturing (LM) philosophy and its tools have been used by many manufacturing industries with different names and forms for efficiently managing the resources. The main focus of lean principles is achieving the most efficient process flow by identifying and eliminating non-value-added (NVA) activities [1]. There are seven original basic wastes defined by LM philosophy, which include transportation, inventory, motion, waiting, overproduction, overprocessing, and defects. The underutilization of people and facilities is also considered as an eighth waste in recent studies [2], [3]. It is essential to improve the production facility of small and medium manufacturing enterprises (SMEs) in India since they contribute to improving the economy of the nation. Over 11 million SMEs in India contribute to approximately 6% of the production of gross domestic products [3]. However, the global manufacturing capabilities of India still need to be investigated. While large manufacturing industries explore a wide range of technological advancements, few organizations lead the market with international competencies in terms of producing high-quality products at a low cost. This scenario confines the SMEs to be less competitive due to inferior facilities and technologies. Hence, SMEs in India still need to improve their productivity, utilization of resources, and performance by eliminating NVAs, wastes, and develop their economic and technological aspects to stay competitive. LM is an important and essential technique to achieve these aspects in Indian SMEs.

Although the Indian government is taking necessary improvements in lean implementation in SMEs, systematic implementation strategies should be adopted to identify and incorporate well-suited lean tools based on the present status of an organization [4]. Therefore, this article presents an integrated framework for selecting the appropriate lean tool(s) using the linguistic opinions of experts and industry persons. The majority of the industries utilizing lean principles are discrete manufacturing industries, service industries, and supply chain firms [1], [5], while it is less common for continuous processing industries such as steel processing.

In the present article, value stream mapping (VSM) is used to identify the wastes and NVAs. The lean tools are selected based on the literature. Further, the multicriteria decision-making (MCDM) tools, respectively, analytic hierarchy process (AHP) and complex proportional assessment of alternatives (COPRAS) are used to prioritize the wastes and lean tools. The main aim of the present article is to make use of fuzzy integrated AHP and COPRAS on the selection of appropriate lean tools and alternatives for an existing manufacturing plant. To exhibit the competence of LM on the performance improvements of manufacturing industries, the following research objectives are framed by the authors.

1) To propose a fuzzy-based framework for the selection of suitable lean tools/alternatives for manufacturing industries.

2) To validate the proposed framework using a case study from the Indian steel processing industry.

3) To check the effectiveness of the framework by comparing present and future state VSM of the case industry.

The rest of this article is organized as follows. Section II presents detailed literature on lean implementation. Section III describes the development of the methodological framework. Section IV provides demonstration of the developed framework in a highly challenging continuous processing industry (i.e., steel rolling mill). Finally, Section V concludes the article.

II. LITERATURE REVIEW

The literature review is performed with the viewpoints of lean implementation in SMEs, tools and techniques, and frameworks adapted for lean projects in manufacturing organizations.

A. Review on Implementation of LM in SMEs

Many research studies have investigated the benefits of implementing lean principles in SMEs through LM frameworks [6]. While LM implementation has reported many challenges, there are many successful case studies found in the literature. Prasad et al. [7] presented a survey-based methodology to identify wastes and lean tools for foundry industries. The survey was performed at 27 foundry industries in India and 17 wastes were identified. The wastes were then prioritized using statistical techniques. The major wastes were then considered for elimination. The article concluded that the wastes should be eliminated gradually in order to stabilize improvement along the way.

In a similar survey-based study, Panwar et al. [8] revealed that LM practices have a strong positive influence on operational performance in areas such as inventory management, on-time delivery, elimination of wastes, cost reduction, and productivity improvement. Few challenges that come as a hindrance during LM implementation in process industries are plant age, size of the plant, lack of supply chain power, lack of financial support, and lack of skilled employees, amongst others. However, the study concluded that smaller firms such as SMEs have greater flexibility to adapt to changes due to their simple organizational structure. In the same way, a survey-based research conducted by Bashar and Hasin [9] indicated a good percentage of lean awareness, but the implementation perspective was not satisfactory due to a lack of training and skills to adapt and implement LM practices.

A two-phase analysis methodology was utilized by Belhadi et al. [10] to evaluate the critical success factors for lean implementation in SMEs. The article identified 27 critical success factors, which were then classified into five groups: policy, funding, culture, market, and implementation and monitoring. Based on the prioritization through AHP, the first category to give attention to was policy and management. The second category was methodology and implementation. When lean tools were systematically selected and properly implemented, there were definite benefits in terms of cost, material, and productivity. Sahoo [11] investigated the application of LM in automobile parts manufacturing SMEs. An in-depth, semi-structured questionnaire-based survey was conducted using 14 automotive SMEs, which were characterized by different types of products. The majority of the organizations surveyed had a good understanding of the LM principles and concepts. However, the lack of organizational culture and management support were the critical factors affecting lean implementation.

B. Review on VSM

There are various lean tools and techniques widely used in industries, such as VSM, 5S, total productive maintenance (TPM), kanban, pull production, kaizen, plan-do-check-act (PDCA), takt time, and standard work [12], amongst others. Certain tools frequently used by most of the lean practicing industries are VSM, 5S, TPM, cellular manufacturing, and work standardization [11]. VSM is used to represent information related to process flow, activities, material movement, and processing times. VSM is mainly used in industries to identify waste and improvement areas [13]. Further, VSM enables an organization to monitor processes relative to both the current/present and future state. VSM also provides a roadmap to streamline the processes by incorporating the proposed changes to achieve the future lean state [14].

Ben Fredj-Ben Alaya [13] stated that VSM became a standard implementation technique for LM in the recent era. It serves as an essential tool to discover wastes and their societal and environmental impacts [15]. Further, Grewal [14] argued that by implementing VSM, even a small industry may produce noteworthy improvements. VSM helps to visualize the beneficial conditions while introducing changes [16]. Kumar and Parameswaran [17] stated that implementation of VSM is carried out mainly to reduce cycle time, improve utilization of facilities, and show productivity improvements from the LM perspective. While VSM does not make any changes directly on the shop floor, it guides decision makers to make changes.

C. Review on Lean Implementation Frameworks

The selection and implementation of lean tools without any guidance or experience is a challenging task. In this context, few frameworks have been developed by researchers to systematically select and implement LM practices in SMEs. Table I provides the lean tools, implementation frameworks developed and used by researchers, and application industries. Most of the frameworks use the relationship between wastes/attributes one on the other to generate relative weights. Further, the correlations of each waste/attribute with the identified lean tools are determined to prioritize the lean tools.

The frameworks developed in previous studies considered the selection of lean tools as an MCDM problem. The techniques include quality function deployment (QFD), failure mode and effects analysis (FMEA), technique for order of preference by similarity to ideal solution (TOPSIS), decision making trial and evaluation laboratory (DEMATEL), AHP, analytic network process, and COPRAS, amongst others. Fuzzy logic is incorporated by a majority of the frameworks in order to eliminate the disadvantages associated with crisp number calculations such as the inability to handle judgments that are vague in nature and the inability to assess uncertainty [18]. The AHP proposed by Saaty...
TABLE I
IMPLEMENTATION FRAMEWORKS DEVELOPED FOR LM IN SMEs

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Frameworks/methodology</th>
<th>Data form</th>
<th>Lean tools/techniques</th>
<th>Industries</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AHP</td>
<td>Fuzzy</td>
<td>Just-in-time (JIT), visual control, continuous improvement</td>
<td>Steel industry</td>
<td>[27]</td>
</tr>
<tr>
<td>2</td>
<td>Standard implementation</td>
<td>Crisp</td>
<td>Production leveling, kaizen</td>
<td>Auto components manufacturing</td>
<td>[28]</td>
</tr>
<tr>
<td>3</td>
<td>AHP-data envelopment analysis (DEA)</td>
<td>Fuzzy</td>
<td>5S, six sigma, cellular manufacturing</td>
<td>Automotive industry</td>
<td>[18]</td>
</tr>
<tr>
<td>4</td>
<td>TOPSIS</td>
<td>Fuzzy</td>
<td>-VSM, 5S, TPM, Value creation, waste elimination, sustain flow</td>
<td>Valve manufacturing</td>
<td>[29]</td>
</tr>
<tr>
<td>5</td>
<td>VSM-QFD</td>
<td>Fuzzy</td>
<td>5S, poka-yoke, kanban, stage wise inspection</td>
<td>Camshaft manufacturing</td>
<td>[31]</td>
</tr>
<tr>
<td>6</td>
<td>QFD-FMEA</td>
<td>Fuzzy</td>
<td>Layout planning, pull production</td>
<td>Plastic water tank production</td>
<td>[4]</td>
</tr>
<tr>
<td>7</td>
<td>VIKOR</td>
<td>Crisp</td>
<td>SMED, group technology, mixed flow production</td>
<td>Yogurt production line</td>
<td>[32]</td>
</tr>
<tr>
<td>8</td>
<td>FMEA</td>
<td>Fuzzy</td>
<td>TPM, kanban, continuous flow, poka-yoke</td>
<td>Auto component manufacturing, casting industry</td>
<td>[17]</td>
</tr>
<tr>
<td>9</td>
<td>FMEA-AHP-QFD</td>
<td>Fuzzy</td>
<td>5S, Kaizen, Layout modification</td>
<td>PVC pipes manufacturing industry</td>
<td>[33]</td>
</tr>
<tr>
<td>10</td>
<td>Delphi method-AHP-FMEA</td>
<td>Fuzzy</td>
<td>5S, TPM</td>
<td>Paper and board manufacturing</td>
<td>[34]</td>
</tr>
<tr>
<td>11</td>
<td>DEMATEL</td>
<td>Fuzzy</td>
<td>Kaizen, 5S, standardization, visual controls</td>
<td>Refrigerator manufacturing</td>
<td>[35]</td>
</tr>
<tr>
<td>12</td>
<td>VSM-root cause analysis based framework</td>
<td>Crisp</td>
<td>5S, kanban, kaizen, poka-yoke, visual controls</td>
<td>Textile industry</td>
<td>[36]</td>
</tr>
</tbody>
</table>
(1980) is effectively used for addressing MCDM problems in many areas such as supply chain [41], risk management [19], construction [40], lean implementation [11], and sustainable selection processes [20]. To address criticisms, such as not being capable of handling vague/hazy thoughts through linguistic opinions, AHP was integrated with fuzzy logic and has been used by a vast number of researchers.

The COPRAS developed by Zavadskas and Kaklauskas [21] is a distinguished MCDM approach to assess and select appropriate alternatives among the available possible alternatives. This method establishes a solution by comparing the direct and proportional ratio of the most excellent solution to the ratio of the ideal-worst solution [22]. It is widely used in complex real-world problems where the attributes conflict with each other. In the conventional method of COPRAS, crisp numbers of the information are considered for the weights of each criterion and ratings of each alternative. FCOPRAS was introduced by Zavadskas and Antucheviciene [23] to handle inaccurate and imprecise judgments by experts. FCOPRAS method considers the dependence between the criteria and alternatives. Also, FCOPRAS is significant in reducing the number of judgments required from experts [24].

FAHP and FCOPRAS combined frameworks have been effectively applied to MCDM problems such as performance measurement, supplier selection, green supplier evaluation, and machine tool evaluation. FAHP is more accurate in weighing the criteria and FCOPRAS is effective in avoiding inconsistencies by normalizing the alternative data [25]. There are several aspects by which the FAHP and FCOPRAS combined framework can be compared with the existing studies.

1) Many LM frameworks developed by previous studies were theoretical and were not substantiated. This makes uncertainty in LM implementation among the practicing managers. Although many researchers have reported the suitability of lean tools to specific manufacturing environments, only a few have sculpted them into a framework [26].

2) Similar established models that use MCDM techniques were LM driver-oriented and emphasize more on the managerial components but little attention has been given to implementation practices.

3) Most of the models listed in Table I were mainly intended to prioritize lean tools based on the weights calculated and not given importance to reduce the inconsistencies that can be done effectively by FCOPRAS.

4) Most studies considered the identification of NVA for the development of LM frameworks but failed to incorporate the role of quality in products and practices. But the developed framework in this article is exercised through a case study to emphasize quality practices also.

Due to the aforesaid comparative advantages, the present work integrates FAHP and FCOPRAS to address the lean tools selection problem.

D. Research Gap

Based on the analysis of the earlier studies, the following research gaps are found.

III. METHODOLOGY

The research methodology adopted for this article is shown in Fig. 1. Based on the gap identified from the literature, a suitable manufacturing organization was selected to conduct the study.

A. Stage 1

After careful understanding of the processes, the current state VSM and plant layout of the organization were drawn along with the appropriate quantifiable information. The various forms of wastes were identified in the present state VSM and layout. The plant layout was drawn to understand the flow of materials and processes and the location of facilities on the shop floor so that unnecessary transportation, if any, could be identified. The lean tools were identified through the literature and with the help of industry experts.

1) From Table I, most of the frameworks have integrated multiple techniques/approaches. It is clear that two or more approaches are required to be integrated to obtain consistent and trustworthy results.

2) From Table I, it is also identified that frameworks that reveal a generic approach for lean tools selection are very less.

3) To the best of the authors’ knowledge acquired through the literature, only a few studies reported on LM implementation in steel production industries in India. Although the integration of AHP and COPRAS under a fuzzy environment has addressed many MCDM problems effectively, the literature does not reveal its application in LM implementation. This has formed a scope for integrating FAHP and FCOPRAS to address the problem of lean tools selection.
To assess and prioritize the identified wastes and lean tools based on their suitability to the case organization, an expert team of three members having more than ten years of experience and excellent knowledge in lean principles was formulated. The team comprises heads of production and quality departments from the industry and one industrial engineering professional. Incorporating the role of quality in product and practices into the model is the major reason for selecting an expert from the quality department. Also, any methodology developed by the industrialists/researchers should be applicable to all types of organizations at all levels. Keeping this criterion in mind, the expert members were selected. A detailed questionnaire was then prepared to assess the identified wastes and lean tools through the linguistic opinions of the expert team. Several brainstorming sessions were conducted to evaluate the data.

B. Stage 2
1) Fuzzy AHP: This article uses the extended analysis method [37] of FAHP to calculate the relative importance of identified wastes with respect to one another. For this reason, pairwise comparison matrices from the expert team members were constituted. The pairwise comparison matrix \( \hat{P} \) for each expert member was constructed using (1). Due to various advantages such as intuitive, easy to employ, and simplicity in computations, triangular fuzzy numbers (TFNs) are used in this present study. The linguistic statements and respective TFNs used for FAHP calculations are given in Table II [38]

<table>
<thead>
<tr>
<th>Linguistic statements</th>
<th>Corresponding TFN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equally important</td>
<td>(1; 1; 3)</td>
</tr>
<tr>
<td>Weakly important</td>
<td>(1; 3; 5)</td>
</tr>
<tr>
<td>Essentially important</td>
<td>(3; 5; 7)</td>
</tr>
<tr>
<td>Very strongly important</td>
<td>(5; 7; 9)</td>
</tr>
<tr>
<td>Absolutely important</td>
<td>(7; 9; 9)</td>
</tr>
</tbody>
</table>

\[
\hat{P} = \begin{bmatrix}
1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\
\tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1
\end{bmatrix}
\]

\[
= \begin{bmatrix}
(1, 1, 1) & (a_{12}, b_{12}, c_{12}) : (a_{1n}, b_{1n}, c_{1n}) \\
(a_{21}, b_{21}, c_{21}) & (1, 1, 1) : (a_{2n}, b_{2n}, c_{2n}) \\
\vdots & \vdots & \ddots & \vdots \\
(a_{n1}, b_{n1}, c_{n1}) & (a_{n2}, b_{n2}, c_{n2}) & \cdots & (1, 1, 1)
\end{bmatrix}
\]

where the element of matrix \( \hat{P} \), \( \tilde{a}_{ij} = (a_{ij}, b_{ij}, c_{ij}) = (1/c_{ij}, 1/b_{ij}, 1/a_{ij}) \) for \( i = 1, 2, \ldots, n, j = 1, 2, \ldots, n, i \neq j \), and \( \tilde{a}_{ij} = (1, 1, 1) \) for \( i = j \). In the same way, a synthetic pairwise comparison matrix was calculated by combining three different matrices formed by the expert team members. The elements \( (\tilde{g}_{ij}) \) from the synthetic pairwise comparison matrix \( \tilde{G} \) were calculated using the following equation:

\[
\tilde{g}_{ij} = (\tilde{a}_{ij}^{1} \times \tilde{a}_{ij}^{2} \times \cdots \times \tilde{a}_{ij}^{E})^{1/N}
\]

where \( N \) is the number of expert team members. Further, the fuzzy geometric mean matrix \( \tilde{m}_{ij} \) is defined using (3) and the fuzzy relative weight of each waste \( \tilde{R}_{i} \) is calculated using (4) [39].

\[
\tilde{m}_{ij} = (\tilde{g}_{i1} \times \tilde{g}_{i2} \cdots \times \tilde{g}_{in})^{1/n}
\]

\[
\tilde{R}_{i} = \tilde{m}_{i} \times (\tilde{m}_{1} + \cdots + \tilde{m}_{n})^{-1}.
\]

The calculated relative weights of each waste are in the form of fuzzy numbers. Therefore, the relative weight of waste \( i \) is \( \tilde{R}_{i} = (L_{R_{i}}, M_{R_{i}}, U_{R_{i}}) \), where \( L_{R_{i}} \) is the lower value, \( M_{R_{i}} \) is the middle value, and \( U_{R_{i}} \) is the upper value. To defuzzify the fuzzy number into crisp numbers, the present study uses the center of area method. The best nonfuzzy performance value (BNP) of a TFN \( \tilde{R}_{i} \) is given by [40]

\[
\text{BNP}_{i} = [(U_{R_{i}} - L_{R_{i}}) + (M_{R_{i}} - L_{R_{i}})] / 3 + L_{R_{i}}.
\]

2) Fuzzy Complex Proportional Assessment of Alternatives: Due to the stated advantages from the literature, the present research work applied FCOPRAS to prioritize the identified lean tools in relation to the wastes identified. The formation of dependence matrices from three expert members was conducted using the linguistic scale given in Table III [41].

In the present article, dependence matrices between wastes and lean tools were developed for all three expert members. Similar to the FAHP method, a comprehensive synthetic/comprehensive dependence matrix \( D \) is determined by combining all three dependence matrices. The resulted fuzzy dependence matrix is in the form of the following equation:

\[
D = \begin{bmatrix}
\tilde{d}_{11} & \tilde{d}_{12} & \cdots & \tilde{d}_{1n} \\
\tilde{d}_{21} & \tilde{d}_{22} & \cdots & \tilde{d}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{d}_{m1} & \tilde{d}_{m2} & \cdots & \tilde{d}_{mn}
\end{bmatrix}
\]

where \( n \) is the number of wastes identified and \( m \) is the number of lean tools identified. Therefore, \( \tilde{d}_{mn} \) is the aggregated dependence value from expert members between the lean tool \( m \) and waste \( n \). The values in the matrix are in the form of TFN. Equation (5) is used to convert the fuzzy values into BNP crisp values and a dependence matrix with crisp numbers \( \hat{D} \) is obtained

\[
\hat{D} = \begin{bmatrix}
\tilde{d}_{11} & \tilde{d}_{12} & \cdots & \tilde{d}_{1n} \\
\tilde{d}_{21} & \tilde{d}_{22} & \cdots & \tilde{d}_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
\tilde{d}_{m1} & \tilde{d}_{m2} & \cdots & \tilde{d}_{mn}
\end{bmatrix}
\]

where \( \tilde{d}_{mn} \) is the defuzzified crisp number of \( d_{mn} \). The next step in the FCOPRAS method is the creation of the normalized
TABLE III
FUZZY SCALE USED FOR FCOPRAS CALCULATIONS

<table>
<thead>
<tr>
<th>Linguistic terms</th>
<th>Corresponding TFN</th>
<th>Reciprocal of TFN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely low dependence (ELD)</td>
<td>(1, 1, 1)</td>
<td>(1, 1, 1)</td>
</tr>
<tr>
<td>Very low dependence (VLD)</td>
<td>(1, 2, 3)</td>
<td>(1/3, 1/2, 1)</td>
</tr>
<tr>
<td>Low dependence (LD)</td>
<td>(2, 3, 4)</td>
<td>(1/4, 1/3, 1/2)</td>
</tr>
<tr>
<td>Moderately low dependence (MLD)</td>
<td>(3, 4, 5)</td>
<td>(1/5, 1/4, 1/3)</td>
</tr>
<tr>
<td>Moderate dependence (MD)</td>
<td>(4, 5, 6)</td>
<td>(1/6, 1/5, 1/4)</td>
</tr>
<tr>
<td>Moderately high dependence (MHD)</td>
<td>(5, 6, 7)</td>
<td>(1/7, 1/6, 1/5)</td>
</tr>
<tr>
<td>High dependence (HD)</td>
<td>(6, 7, 8)</td>
<td>(1/8, 1/7, 1/6)</td>
</tr>
<tr>
<td>Very high dependence (VHD)</td>
<td>(7, 8, 9)</td>
<td>(1/9, 1/8, 1/7)</td>
</tr>
<tr>
<td>Extremely high dependence (EHD)</td>
<td>(8, 9, 9)</td>
<td>(1/9, 1/9, 1/8)</td>
</tr>
</tbody>
</table>

The defuzzified-dependence matrix $\bar{D}$. The normalization of matrix element $\bar{d}_{ij}$ is calculated using

$$\bar{d}_{ij} = \frac{\tilde{d}_{ij}}{\sum_{j=1}^{n} d_{ij}}, \quad i = 1 \text{ to } m \text{ and } j = 1 \text{ to } n. \quad (8)$$

Therefore, the resulting normalized matrix is in the form

$$\bar{D} = \begin{bmatrix}
\frac{d_{11}}{d_{1n}} & \frac{d_{12}}{d_{1n}} & \cdots & \frac{d_{1n}}{d_{1n}} \\
\frac{d_{21}}{d_{2n}} & \frac{d_{22}}{d_{2n}} & \cdots & \frac{d_{2n}}{d_{2n}} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{d_{m1}}{d_{mn}} & \frac{d_{m2}}{d_{mn}} & \cdots & \frac{d_{mn}}{d_{mn}}
\end{bmatrix}. \quad (9)$$

The weighted normalized dependence matrix $\bar{D}$ is then developed by multiplying its elements with the relative weights computed from FAHP. It is calculated as

$$\bar{d}_{ij} = \bar{d}_{ij} \times w_j, \quad i = 1 \text{ to } n \text{ and } j = 1 \text{ to } m \quad (10)$$

where $w_j$ is the relative weight calculated from FAHP for the $j$th waste. The resulting normalized matrix is in the form of

$$\bar{D} = \begin{bmatrix}
\frac{d_{11}}{w_{11}} & \frac{d_{12}}{w_{11}} & \cdots & \frac{d_{1n}}{w_{11}} \\
\frac{d_{21}}{w_{21}} & \frac{d_{22}}{w_{21}} & \cdots & \frac{d_{2n}}{w_{21}} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{d_{m1}}{w_{m1}} & \frac{d_{m2}}{w_{m1}} & \cdots & \frac{d_{mn}}{w_{m1}}
\end{bmatrix}. \quad (11)$$

Based on the FCOPRAS procedure, the wastes should be grouped into two categories, namely more preferable and less preferable. The weight of the more preferable category should be maximized and the less preferable category should be minimized. The sums of normalized values of more preferable $P_i$ and less preferable $R_i$ categories can be calculated using (12) and (13)

$$\bar{d}_{ij} = \frac{\tilde{d}_{ij}}{\sum_{j=1}^{n} d_{ij}}, \quad i = 1 \text{ to } m \text{ and } j = 1 \text{ to } n. \quad (8)$$

$$P_i = \sum_{j=1}^{k} \bar{d}_{ij} \quad (12)$$

where $k$ is the number of more preferable wastes. It is usually practiced that wastes under the more preferable category are placed in the first several columns and the less preferable wastes are placed in latter columns to ensure the grouping of criteria (in our case, wastes)

$$R_i = \sum_{j=k+1}^{n} \bar{d}_{ij} \quad (13)$$

where $(n-k)$ is the number of less preferable wastes. Then, the final weight of each lean tool is calculated using

$$Q_i = P_i + \frac{R_{\min}}{R_{\max}} \sum_{i=1}^{m} \frac{R_i}{R_{\max}} \quad (14)$$

where the utility degree of each tool is

$$N_i = \frac{Q_i}{Q_{\max}} \times 100\%. \quad (15)$$

C. Stage 3

Lean tools are prioritized based on the final weight calculated using (14), and a top few tools were chosen to implement in the case organization. The tools that have an immediate effect were incorporated in the case organization and the tools that take time to show the positive effects were predicted. The proposed changes were then incorporated into the future state VSM. Finally, to visualize the positive effects of LM, the future state VSM was compared to the current state VSM.

IV. CASE STUDY

The growing demands of steel around the world create limitations on the primary steel production sector. Steel rolling mills are an unavoidable connection in the supply chain of the steel industry since they meet different requirements. Due to its importance and lack of LM implementation studies in the steel industry, the case study in this article was carried out in a steel rolling mill located in Tirupur, Tamil Nadu, India. The organization was established in 1992 and is presently the leading manufacturer of thermomechanically treated (TMT) bars in the zone. The organization manufactures TMT bars of various sizes, such as 8, 10, and 12 mm diameter. The company
employs approximately 120 people including workers, supervisors, engineers, and top management. Given the culture of the organization, it is highly adaptable to implementing changes according to lean principles.

A. Current State Plant Layout and VSM

The plant layout was drawn to analyze the process flow, location of machines, material handling, inventory, and any hidden wastes, such as unnecessary motion or transportation, as shown in Fig. 2. The material flow starts from raw material inventory through coal furnace, roughing stand, intermediate stand, finishing stand, and ends at storing and dispatch. The different types of arrows indicate different material flows such as raw material, coal flow, ash flow, and in-process material flow. Microsoft Office Visio was used to draw the plant layout. The current state layout also helps to visualize the utilization of the shop floor area, which needs improvement/change.

The existing processes and related information were then mapped to illustrate the current state VSM. Information such as change over time, process cycle time (CT), delay time between the processes, types of wastes, inventory, available time (AT), and uptime (UT) are provided in the current state VSM shown in Fig. 3. Vendors supply mild steel ingots and billets as raw materials for TMT bars on a daily basis. The material goes under various operations while transforming into TMT bars. The flow of the TMT bar manufacturing process starts with reheating raw material, roughing, intermediate rolling, finished shape rolling, cutting, and inspection, and then ends with dispatching. The value-added (VA) and NVA times are noted on the current state VSM (see Fig. 3). Push production is currently followed in the organization. Production time was calculated as follows [42]:

1) Total operating time = 12 h × 60 min = 720 min
2) Two breaks (15 min each) = 2 × 15 min = 30 min
3) Lunch break = 45 min
4) Actual AT for production = (720 - 30 - 45) = 645 min.
Therefore, a total of 645 min is the actual AT for production. Takt time is an important indicator of the performance of any manufacturing industry [2]. Given the case organization’s present conditions, it is able to produce 450 pieces of TMT bars per day. The takt time for the case organization is calculated as follows:

1) Takt time $= \frac{AT}{customer \ demand}$
2) Takt time $= \frac{645 \ min}{450 \ pieces}$
3) Takt time $= 1.43 \ min/piece$.

B. Identification of Wastes and Lean Tools/Alternatives

The wastes were then systematically identified and reported by industry professionals during frequent visits to the case organization to analyze the VSM and layout. From the current state analysis, a missed roll was identified as a primary waste since it leads to a large quantity of material waste. Using root cause analysis, it was determined that miss roll occurs due to improper maintenance of the roller conveyor and inadequate reheating of steel billets. The material discarded from the miss roll defect must be reworked to form billets, which consumes resources and incurs additional cost, transportation, and effort.

The case organization currently uses a push production system, irrespective of the daily ordered quantity of TMT rods produced with their production capacity. This overproduction results in a large amount of inventory, which consumes more space for storage. Further, holding the inventory for longer periods of time in an open area results in corrosion, which affects the product quality.

Another significant waste in the plant is the variation in the proper weight of the billets. When converting the entire volume of a billet into a standard length of the bar, overweighted billets produce additional length and underweighted billets produce inadequate length. The longer bars are usually cut and directed to rework. Another cause for this size issue is the improper selection of the billets/ingots. Further, insufficient quality of billets produces more scale waste during the heating process and reduces the volume of billet. When more material sticks to the rollers during the rolling process, it affects the rolling process and the quality of the TMT rods.

With the help of direct observation, the quantifiable wastes generated per operating shift are given in Table IV. Scrap, higher setup time, machine breakdown, and low productivity are the main reasons for continuous improvement. The solution to these waste problems lies in the proper training and supervision of workers. Further, efficient material flow and transportation reduce the need for additional cost, transportation, and effort, which improves the efficiency of the production process.

Another significant waste in the plant is the variation in the size of the bars. The variation in length occurs due to the improper weight of the billets. When converting the entire volume of a billet into a standard length of the bar, overweighted billets produce additional length and underweighted billets produce inadequate length. The longer bars are usually cut and directed to rework. Another cause for this size issue is the improper selection of the billets/ingots.

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TABLE IV
QUANTITY OF WASTES IDENTIFIED

<table>
<thead>
<tr>
<th>Waste type</th>
<th>Types of waste</th>
<th>Quantity (kg) per working shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale waste</td>
<td>Miss roll defect</td>
<td>1100</td>
</tr>
<tr>
<td>Defect</td>
<td>Corrosion defect</td>
<td>1250</td>
</tr>
<tr>
<td>Size variation</td>
<td>920</td>
<td></td>
</tr>
</tbody>
</table>

The implementation proposals are discussed in the following sections. The future state VSM is illustrated in Fig. 4.

1) PDCA and Selection of Bar: PDCA was initially implemented in the raw material procurement section to ensure that the correct specifications of raw materials are received. This is because the size variation waste mainly depends on the raw material weight. Table VII provides the minimum and maximum weight of the TMT bar compared to the standard weight. PDCA initiates the problem-solving process. PDCA starts with analyzing the problem and ends with providing an alternate effective solution(s). Based on the outcomes of a PDCA meeting among the expert members, it was suggested to select raw material according to the weight calculation method for producing quality bars in order to also eliminate variation defects. The average minimum and maximum weight per unit length of bars are measured from the samples of different shifts. These weights are compared with the standard weight calculated as

\[
\text{Weight per unit length of bar} \ (\text{Kg/m}) = \text{density of bar} \times \text{cross-sectional area of bar} = \left(7850 \times 3.14 \times D^2\right) / \left(4 \times 10^6\right). \tag{16}\]

The weight raw material can be selected according to the required overall length of the bar. Also, it is suggested to frequently check the quality of billets received to ensure the minimal formation of scale. By following these two proposals, the changes were implemented and the waste-related information was noted in the future state VSM (see Fig. 4).

2) TPM and 5S: Currently, the case organization follows no standard maintenance procedure for all of its facilities and equipment, which causes frequent failure of machine elements. Since a hot rolling mill is a continuous production process, repairing the failures sometimes leads to a complete breakdown of an entire production facility. This is a great loss to the case organization in terms of cost, productivity, power, and efforts. Therefore, as suggested by this article, TPM was an essential tool to be incorporated in the case organization. The failure of a conveyor chain due to the lack of maintenance generates a miss roll defect, which is a significant loss to the case organization. This waste can be minimized by following periodic and planned maintenance with the help of maintenance charts and procedures.

The present environment on the manufacturing floor does not motivate or encourage the complete involvement of manufacturing employees. The production environment is dusty and polluted. Cleanliness is most needed in the case organization in order to have a healthy and motivating environment for the employees. The implementation of 5S helps to arrange the tools and equipment in an order that eases the storing and retrieving of these items. In addition, 5S attributes to the effectiveness of the production process. The decision makers of the case organization agreed to implement TPM and 5S in the near future.

3) Standardization: Standardization was also suggested to keep the organization successful in the competitive environment as it provides an overall improvement in the production process by benchmarking competitors. Initially, standardization was applied to the furnace section and the results were noted.
TABLE V
NORMALIZED DEPENDENCE/DECISION MATRIX

<table>
<thead>
<tr>
<th>Wastes/ Tools</th>
<th>Corrosion defect</th>
<th>Miss roll defect</th>
<th>Size variation</th>
<th>Scale waste</th>
<th>Scrap setup time</th>
<th>High breakdown</th>
<th>Low productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanban</td>
<td>0.019</td>
<td>0.006</td>
<td>0.004</td>
<td>0.004</td>
<td>0.009</td>
<td>0.007</td>
<td>0.002</td>
</tr>
<tr>
<td>PDCA</td>
<td>0.083</td>
<td>0.015</td>
<td>0.011</td>
<td>0.007</td>
<td>0.014</td>
<td>0.016</td>
<td>0.008</td>
</tr>
<tr>
<td>IQC</td>
<td>0.019</td>
<td>0.006</td>
<td>0.018</td>
<td>0.029</td>
<td>0.013</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>Heat treatment</td>
<td>0.032</td>
<td>0.022</td>
<td>0.004</td>
<td>0.005</td>
<td>0.015</td>
<td>0.013</td>
<td>0.006</td>
</tr>
<tr>
<td>TPM</td>
<td>0.074</td>
<td>0.012</td>
<td>0.012</td>
<td>0.004</td>
<td>0.008</td>
<td>0.011</td>
<td>0.010</td>
</tr>
<tr>
<td>5S</td>
<td>0.107</td>
<td>0.015</td>
<td>0.015</td>
<td>0.005</td>
<td>0.004</td>
<td>0.007</td>
<td>0.003</td>
</tr>
<tr>
<td>Kaizen</td>
<td>0.114</td>
<td>0.013</td>
<td>0.008</td>
<td>0.004</td>
<td>0.004</td>
<td>0.009</td>
<td>0.001</td>
</tr>
<tr>
<td>Standardization</td>
<td>0.088</td>
<td>0.011</td>
<td>0.004</td>
<td>0.006</td>
<td>0.010</td>
<td>0.015</td>
<td>0.005</td>
</tr>
<tr>
<td>Facility planning</td>
<td>0.060</td>
<td>0.004</td>
<td>0.010</td>
<td>0.020</td>
<td>0.008</td>
<td>0.011</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Fig. 4. Future state VSM.

The furnace is the source of heat energy for reheating the raw material, ingots, or billets to begin the production process. Heat is the primary energy source in any steel roll mills. The case organization uses a coal furnace to reheat raw material. In the reheating process, initially, the billets are heated to 1100 to 1200 °C and the raw material becomes more ductile. The raw material at red hot temperature is then sent to a series of rolling mills to be elongated with the desired shape. Presently, there is little attention given to monitoring the reheating temperature at the coal furnace. Due to insufficient heat supplied to the raw material, the forming process becomes tough for the rollers. The increased load on the rollers causes distortion and leads to frequent failures, which also generates miss roll defects. Similar to PDCA, a standard temperature was selected and maintained and the results are noted in future state VSM (see Fig. 4).

After the series of rolling processes, the elongated bars are sent to a special heat treatment process with three stages. The first stage is quenching with water, which rapidly cools the surface...
to make sure the TMT bar’s ductility. During the quenching process, only the surface becomes martensite. The core remains austenite. In the second stage, the bars are exposed to the air to allow self-tempering. In this process, the surface becomes hard and tough. In the third stage, the bars are cooled in a cooling tank where the core is transformed from austenitic to ductile ferrite pearlite. The temperatures in all of the stages should be uniformly maintained throughout the entire production process as a part of standardization implementation to ensure the quality of the TMT bars. Since the standardization tool covers temperature control in both reheating of billets and thermax process, the need for an alternative solution “heat treatment” was not required and also it was not in the prioritized list.

4) Kaizen: Many kaizen initiatives were implemented in the plant. In the electrical control room, there were no electrical resisting mats provided on the floor. This sometimes becomes a risk for the employees entering into the control room. As a kaizen event, thick floor mats were installed to ensure operator safety.

The final stage of the TMT bar cooling process was completed inside the water tank and then the TMT bars are stacked and stored in the open space without any support at the bottom. Also, the bars are stored and retrieved randomly. As a kaizen event, it was suggested to add suitable coolant oil (e.g., APEX 7900 EP semi-synthetic) to the water tank. The coolant oil creates a layer inside the water tank and then the TMT bars are stacked and stored. The case organization agreed to install closures for the finished product inventory.

5) Takt Time: There are performance indicators for manufacturing industries to measure the effectiveness of a production process. Takt time is one of the measures to monitor productivity [43]. After the future state map was drawn with the observed information, the takt time of the future state is calculated as follows:

\[
\text{takt time} = \frac{\text{available production time/customer demand}}{\text{availability}} = \frac{645 \text{ min/475 pieces}}{1.35 \text{ min/piece}}
\]

F. Comparison of Present and Future State

Notable changes were made to the VSM based on the observations during LM implementation. In total, nine LM tools were identified and only five were systematically selected from FAHP-COPRAS-based methodology for implementation. Three lean tools, namely, PDCA, standardization, and kaizen, were implemented. Another two tools, TPM and 5S, are yet to be implemented. LM tools aim to resolve wastes such as miss roll, size variation, scale, corrosion, high setup time, machine breakdown, and low productivity. The future state VSM was developed by observing the activities closely after lean implementation. A comparison of the current and future state for the present case study is given in Table VIII.

From Table VIII, it is evident that considerable material wastes were reduced due to lean initiation. The results were measured for one-day production and compared to the current state. Scale waste, miss roll defects, size variation defects, and corrosion defects were reduced by 50%, 72.7%, 62%, and 100%, respectively. Takt time, as a measure of productivity, was also improved by 5.6%. These improvements were obtained by the implementation of LM tools directly. A few of the other wastes such as scrap, high setup time, and machine breakdown will also be impacted by implementing lean tools. The implementation of TPM is expected to reduce machine breakdown and scrap. Similarly, standardization is expected to reduce setup time by training employees. In the long run, these improvements will yield considerable improvements to the case organization from lean implementation.

G. Managerial Implications

The organizations similar to the case industry considered in this research work generally have the same kind of process flow. The findings from this case study are very important to the practicing managers of a similar organization to know various types of wastes and to eliminate them effectively. LM principles are time consuming to implement and to see the outcome which is a challenging task for managers to get effective results. It needs a better understanding of the existing process flow and its VA and NVA components.

The present article explores the suitable lean practices for those industries that will further help the managers to easily target the wastes. Another challenge is the conversion of necessary functions into labor understandable instructions. It is essential to educate the laborers with basic techniques and the importance of suggested practices. The industrial practitioners will furthermore realize the importance of VSM in monitoring and
improving the existing process flow. Continuously practicing them would lead to a change in organizational culture that will increase competitiveness.

V. CONCLUSION, LIMITATIONS, AND DIRECTIONS FOR FURTHER RESEARCH

The main contribution of this article is to propose a distinctive framework based on FAHP and FCOPRAS approach to prioritize the appropriate lean tools for manufacturing enterprises. The usefulness of the developed framework was validated through a case study from an Indian steel processing industry. A hot steel rolling mill has many challenges in implementing lean principles due to continuous and large production. In this article, the identification of wastes in steel roll mills was investigated by close observation and the use of VSM. The wastes identified are corrosion defect, miss roll defect, size variation, scale waste, scrap, high setup time, machine breakdown, and low productivity. Lean tools/alternatives were selected with the help of the literature and expert opinion as kanban, PDCA, IQC, heat treatment, TPM, 5S, kaizen, standardization, and facility planning. The developed framework was adapted to prioritize the selected lean tools. Based on the order of ranking, the top few lean tools, namely, PDCA, 5S, kaizen, standardization, and TPM were implemented and the observed results were recorded in the future state VSM. A comparison of the present and future state VSM indicated significant reductions in the wastes such as scale (50%), miss roll (72.7%), size variation (61.9%), and corrosion (100%). Additionally, improvements in setup time, machine breakdown, and scrap are also expected in the long run.

The decision makers and production supervisors were ensured these productivity and quality improvements of the case industry. This developed framework facilitates the industrial practitioners, decision makers, academic researchers, and the lean consultants to select and implement LM practices within their organization. Thus, the presented framework contributes to the sustainability and advancements of lean projects.

The research work involved one case study, which is a major limitation of the present article. This framework can be applied to many similar case industries to check its generic application. Also, the framework is highly dependent on the knowledge of participating expert members. Hence, only the industries with expert members having a deeper understanding of the existing process flow, lean principles, and optimization tools can easily adopt this framework. Future research should consider cost-saving studies to foresee the financial impact on business planning. In addition, the systematic selection methodology can be studied in other continuous production industries, such as plastics processing, and chemical and petroleum industries in the future.

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