A new hybrid method for manufacturing sustainability performance assessment: a case study in furniture industry

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ABSTRACT
Manufacturing sustainability performance evaluation is critical for improving the production line’s performance. Three aspects involved in manufacturing sustainability are economic, social, and environmental. This research aims to create a new framework for assessing the Manufacturing Sustainability Score (MSS) based on the lean concept. A hybrid method involving the Delphi, Dematel-Analytical Network Process (ANP), Sustainability Value Stream Mapping (VSM), and Traffic Light System is proposed. The proposed framework is applied to a case study in the furniture industry, and the results demonstrate that the new framework can assess manufacturing sustainability performance. A case study’s manufacturing sustainability score is 66.97 percent. It demonstrates that the company’s performance is moderate and could be improved. The managerial and academic implications are also presented in this study.

1. Introduction

Population growth, resource depletion, and environmental degradation have all become significant challenges for humans in recent decades (Zhu et al., 2020). The most common environmental issues are resource depletion, increased pollution, and ecological degradation (Sultan et al., 2021; Utama, Widodo, Ibrahim, Dewi et al., 2020). It has prompted businesses to incorporate environmental management concerns into their strategic plans (J. K. Y. J. K. Y. Lee et al., 2021). Waste, toxic chemicals, and greenhouse gas emissions from the manufacturing process all contribute to the manufacturing industry’s environmental impact (Ibrahim et al., 2020; Mohammad Ebrahimii & Koh, 2021). This issue causes stakeholders to be concerned about environmental issues (Helleno et al., 2017; Utama et al., 2022). As a result, eliminating environmental pollution and achieving sustainable development is a corporate social responsibility (Simpson, 2012). The concept of sustainable manufacturing refers to a manufacturing system process that takes into account economic, environmental, and social factors (Machado et al., 2020). This concept aims to produce products in a sustainable manner while maintaining global competitiveness and facing the most recent challenges and problems (J. Y. Y. Y. Lee et al., 2014). This concept necessitates the use of more environmentally friendly processes and
materials in the production of sustainable products, which is an essential component of sustainable manufacturing (Pusavec et al., 2010). Manufacturing sustainability should be assessed to ensure that sustainable manufacturing is achieved (Cherrafi et al., 2016). Therefore, businesses must abandon traditional techniques that only emphasize cost reduction and efficiency improvement without considering the environmental and social impacts of their operations (Faulkner & Badurdeen, 2014).

Some researchers have contributed to corporate sustainability performance measurement (Searcy, 2012). The researchers proposed framework is used for corporate reporting (Moldavska & Welo, 2019). However, this framework does not generate useful information for shop-floor decision-makers at the internal and production line levels. Currently, research into manufacturing sustainability studies is rarely conducted on the shop floor (Patalas-Maliszewska et al., 2022; Swarnakar et al., 2021). Previous research suggests a conceptual manufacturing sustainability assessment framework (Swarnakar et al., 2022). However, it is difficult to apply in industries with varying characteristics. As a result, in order to measure sustainability performance at the manufacturer level, different frameworks and indicators for assessing manufacturing sustainability must be considered from a technical standpoint (Theng et al., 2021). J. Y. J. Y. Lee et al. (2014) provided a shop-floor index based on engineering principles to measure a facility’s sustainable performance. Huang and Badurdeen (2018) proposed a similar method for evaluating the success of sustainable manufacturing in a production line. However, due to a lack of research, the mapping of sustainable manufacturing in the production line is not presented. In fact, visualizing the production process at each work station assists decision-makers in making better sustainability decisions (Sri Hartini et al., 2017b). Hence, a new methodology is required to map and measure sustainable manufacturing performance at the production line level based on economic, social, and environmental variables.

Value stream mapping (VSM) is a mapping tool used by manufacturers to track and improve production line performance (Theng et al., 2021; Utama et al., 2016). VSM determines whether or not an activity is value-added at each stage of production. Traditional VSM does not consider environmental and social issues when mapping the production process (Dewi et al., 2021; Sri; Hartini et al., 2017b). Instead, it focuses on mapping economic aspects such as inventory, time, transportation, and defects (Schoeman et al., 2021). As a result, conventional VSM does not take into account sustainability characteristics such as environmental and social aspects of manufacturing companies. Brown et al. (2014) created the Sustainable-VSM framework for mapping on the production line. Several other researchers use sustainable-VSM in the furniture manufacturing industry (Sri Hartini et al.), electronics (Faulkner et al.) (Sri Hartini et al.), manufacturing (Mishra et al., 2020), and textiles (S. Hartini et al., 2021) to map performance in each workstation and process. Unfortunately, the sustainable VSM tool cannot calculate the overall manufacturing sustainability performance index. The total performance score in sustainable manufacturing must be measured precisely using appropriate indicators. For this reason, Sri Hartini, Ciptomulyono, Anityasari et al. (2020) proposed a methodology for measuring the new manufacturing sustainability index based on appropriate indicators and indicator weights based on sustainable VSM mapping. To our knowledge, only Sri Hartini, Ciptomulyono, Anityasari et al. (2020) research has used sustainable VSM to measure manufacturing sustainability scores based on indicator weights. This study, however, ignores the relationship between indicators.
Each indicator has a relationship that influences the indicator’s weight (Liu et al., 2021; Quezada et al., 2018). Therefore, when evaluating performance, the relationship between the indicators of manufacturing sustainability must be investigated.

Based on the gaps and research opportunities described in the previous paragraph, Manufacturing Sustainability Performance Assessment (MSPA) needs to consider the relationship between manufacturing sustainability indicators. Therefore, in this study, the research goals (RG) are as follows:

RG 1. Develop a new MSPA framework by considering the interrelationships between manufacturing sustainability indicators.

RG 2. Evaluating the performance of manufacturing sustainability based on case studies in furniture industry by considering the relationship between manufacturing sustainability indicators.

Based on these objectives, a new framework is proposed, starting with the identification of indicators and the determination of relevant indicators. Furthermore, an assessment of indicator linkage is determined, followed by indicator weighting based on the relationship indicator. The overall manufacturing sustainability score assessment is based on sustainable VSM mapping and indicator weighting. A case study in the furniture industry was also used to evaluate the performance of manufacturing sustainability. Therefore, it is clear that this research makes a real contribution to science by providing a new framework for assessing manufacturing sustainability performance that considers the interrelationships between manufacturing sustainability indicators. Furthermore, this study also evaluates the furniture industry’s manufacturing sustainability performance.

The remainder of this article is as follows: The second section is a review of the literature. Section 3 introduces the proposed MSPA framework. Section 4 discusses how the proposed framework was applied to a case study. Section 5 describes the results, discussion, and practical managerial implications. This article concludes with a conclusion and future research.

2. Literature review

This section provides a literature review based on previous research on manufacturing sustainability assessment. Elkington (1998) proposed a framework for assessing sustainability that is based on the Triple Bottom Line (TBL). TBL is a framework for measuring an organization’s performance by taking three factors into account: economic, social, and environmental. Rogers and Hudson (2011) refer to this factor as an indicator of sustainable development.

Appropriate TBL sustainability indicators are critical in assessing manufacturing sustainability (Saavalainen et al., 2017). However, inappropriate indicators can provide operational managers with less useful information regarding the performance of the manufacturing process. Table 1 summarizes some research on MSPA. It demonstrates that MSPA research is dominated by production flow mapping and MSPA score assessment, which were investigated separately. MSPA, on the other hand, can be evaluated using production flow mapping (Sri Hartini et al.). Furthermore, previous research has a tendency to select indicators based on theoretical indicators. As a result, some indicators become less relevant to the case study issue. Furthermore, previous studies ignored the interdependence of TBL indicators. As a result, it affects the weight of the TBL
Table 1. Summary of Manufacturing Sustainability Assessment Research.

| Study                                | Rating Score | Mapping | Indicator selection process | Interrelation indicators | Indicator | Applications | Tools          |
|--------------------------------------|--------------|---------|------------------------------|--------------------------|-----------|--------------|----------------|
| Brown et al. (2014)                  | -            | V       | Theoretical                  | -                        | TBL       | Electronic   | VSM            |
| Castiglione et al. (2022)            | V            | -       | Theoretical                  | -                        | Economic, Environmental Manufacturing MEIO |
| Paju et al. (2010)                   | -            | V       | Theoretical                  | -                        | Environmetal | Not Clear   | LCA, VSM        |
| Bhadu et al. (2022)                  | V            | -       | Empirical                    | -                        | Economic   | Manufacturing | AHP            |
| Faulkner and Badurdeen (2014)        | -            | V       | Theoretical                  | -                        | TBL       | Electronic   | VSM            |
| Helleno et al. (2017)                | -            | V       | Theoretical                  | -                        | TBL       | Cosmetic     | VSM            |
| Sri Hartini et al.                   | -            | V       | Empirical                    | -                        | TBL       | Furniture    | VSM            |
| Huang and Badurdeen (2018)           | V            | -       | Theoretical                  | -                        | TBL       | Electronic   | AHP            |
| Garza-Reyes, Kumar et al. (2018)     | -            | V       | Theoretical                  | -                        | TBL       | Mining       | VSM            |
| Bait et al. (2020)                   | -            | V       | Theoretical                  | -                        | TBL       | Manufacturing | Simulation, VSM |
| Swarnakar et al. (2021)              | -            | V       | Empirical                    | -                        | TBL       | Manufacturing | VSM            |
| Patalas-Maliszewska et al. (2022)    | V            | -       | Theoretical                  | -                        | TBL       | Manufacturing | Fuzzy AHP, Decision Tree AHP, VSM, TOPSIS |
| Soltani et al. (2020)                | V            | -       | Theoretical                  | -                        | TBL       | Gas bottle   | AHP, VSM, TOPSIS |
| Sri Hartini, Ciptomulyono, Anityasari et al. (2020) | V | V       | Empirical                    | -                        | TBL       | Furniture    | Delphi, AHP, VSM |
| This Research                        | V            | V       | Empirical                    | V                        | TBL       | Furniture    | Delphi, Dematel, ANP, VSM |

indicator used for MSPA, which is less important. To provide appropriate information to operations managers, the interrelationships between TBL indicators must be considered in order to assess sustainable manufacturing performance.

Another gap in MSPA is that this problem is widely used in the manufacturing and electronics fields. However, this issue is still understudied in the furniture industry. To fill the void, this study proposes MSPA based on process flow mapping in the furniture industry, which includes interrelationships between TBL indicators. Based on empirical studies, this study proposes the TBL indicator used in this study. Furthermore, the manufacturing sustainability rating score is determined by the mapping results of each TBL indicator in each process.

The Delphi method is proposed as a method for identifying relevant indicators. The Delphi method is simple to use to evaluate the relevance of indicators and criteria applied to various sustainable development issues, such as MSPA (Sri Hartini, Ciptomulyono, Anityasari et al., 2020) and sustainable supplier selection (Cherier & Meliani, 2019). The Dematel-ANP procedure was proposed to evaluate the interrelationship and indicator weighting of indicators. Dematel-ANP is a popular method for assessing the interrelation
of indicators and indicator weighting in a variety of issues, such as green supplier selection (Utama, Maharani et al., 2021; Utama, Putri et al., 2021), sustainable supply chain performance (Leksono et al., 2019; Rao, 2021), and mapping strategy (Ocampo et al., 2020). In addition, sustainable VSM was selected because it is a comprehensive procedure for mapping production line indicators (J. K. Y. J. K. Y. Lee et al., 2021; Soltani et al., 2020). In the following section, the MSPA framework is described in detail.

3. Framework proposed MSPA

In this section, the proposed MSPA framework is proposed to assess the manufacturing sustainability score. Figure 1 shows the proposed MSPA framework. The following subsection describes the five major stages of MSPA.

![Diagram of the proposed MSPA framework](image-url)

**Figure 1.** Proposed MSPA Framework.
Table 2. Manufacturing sustainability indicators based on literature review.

| Factors     | Indicators                                                                 | References                                      |
|-------------|-----------------------------------------------------------------------------|------------------------------------------------|
| Economic    | Cost                                                                        | (Hartini, Ciptomulyono, Anityasari et al., 2020; Helleno et al., 2017; Torres & Gati, 2009; Vinodh et al., 2014) |
| Quality     |                                                                             | (Hartini, Ciptomulyono, Anityasari et al., 2020; Sparks, 2014) |
| Inventory   |                                                                             | (Atieh et al., 2016; Faulkner & Badurdeen, 2014; Hartini, Ciptomulyono, Anityasari et al., 2020; Helleno et al., 2017; Sparks, 2014; Vinodh et al., 2014) |
| Time        |                                                                             | (Faulkner & Badurdeen, 2014; Feame & Norton, 2006; Garza-Reyes, Romero et al., 2018; Sri Hartini et al., 2017; Hartini, Ciptomulyono, Anityasari et al., 2020; Paju et al., 2010) |
| Environment | Energy                                                                     | (Hartini, Ciptomulyono, Anityasari et al., 2020; Helleno et al., 2017; Torres & Gati, 2009; Vinodh et al., 2014) |
|             | Material                                                                   | (Hartini, Ciptomulyono, Anityasari et al., 2020; Helleno et al., 2017; Torres & Gati, 2009; Vinodh et al., 2014) |
|             | Waste                                                                      | (Hartini, Ciptomulyono, Anityasari et al., 2020) |
| Social      | Employee training                                                          | (Hartini, Ciptomulyono, Anityasari et al., 2020) |
|             | Safety level                                                               | (Hartini, Ciptomulyono, Anityasari et al., 2020; Helleno et al., 2017) |
|             | Health level                                                               | (Hartini, Ciptomulyono, Anityasari et al., 2020) |
|             | Satisfaction level                                                         | (Hartini, Ciptomulyono, Anityasari et al., 2020) |

3.1. Indicator collection and indicator formula

The proposed framework’s initial stage begins with the compilation of efficiency indicators and formulas for each TBL indicator. The indicators are gathered by conducting a literature review on manufacturing sustainability in the production line. Table 2 shows the manufacturing sustainability indicators that emerged from the literature review. Table 3 also contains the performance formula for each indicator.

3.2. Relevant indicators selection via the Delphi method

Based on the TBL review literature indicators, the next step is the selection of industry-relevant indicators. Each indicator is assessed by industry experts using the Delphi method. The Delphi method is a group process for gathering expert opinions in a particular field (Yousuf, 2007). According to Noly (2018), the Delphi method allows experts to discuss and make decisions without having to meet. This method effectively solves problems based on expert opinion (Widiasih et al., 2015). The literature recommends 3 to 18 experts on the Delphi panel (Okoli & Pawlowski, 2004; Rowe & Wright, 1999). The Delphi method has been used for various issues in sustainability development, including the determination of indicator weights (Azevedo & Barros, 2017) and the green supply chain (Jiang et al., 2018).

In the Delphi method, the relevance of indicators to the company’s sustainability is determined by the average method (Feil et al., 2015). The cut-off of the relevant indicators is based on the analysis of weight average (WA) and level of consensus (LC; Feil et al., 2015; Miller, 2001). Hartini, Ciptomulyono, Anityasari et al. (2020) selected an indicator with WA > 4.0 and LC > 0.7. The formulas for WA and LC are presented in Equations 1 and 2. Where SRi shows the relevance assessment score of the i-th respondent and Nr is the number of respondents. The number of respondents who stated they were relevant was notated as FNR. The Delphi method uses five relevance rating scales
Table 3. Performance formulas for each indicator.

| No. (i) | Indicators (Input) | Formula | References |
|---------|--------------------|---------|------------|
| 1 | Cost (Rp) | CE = Cost efficiency<br>VAC = Cost of activities that have added value<br>NVAC = Cost of non-value added activities<br>TC = Total cost<br>n = process to n<br>CE = \frac{VAC}{TC} <br>VAC = \sum_{i=1}^{n} (VAC_i)<br>NVAC = \sum_{i=1}^{n} (NVAC_i)<br>TC = VAC + NVAC | Vinodh et al. (2014) |
| 2 | Quality (part) | QE = Quality efficiency<br>ND = Number of defects<br>TM = Total material<br>QE = 1 - \frac{(ND)}{TM} | Sparks (2014) |
| 3 | Inventory (unit) | IE = Inventory efficiency<br>NI = Total inventory<br>TM = Total material<br>IE = \frac{NI}{TM} | Faulkner and Badurdeen (2014) |
| 4 | Time (menit) | TE = Time efficiency<br>VAT = Time in value-added activities<br>TT = Total time<br>NVAT = Time in non-value added activities<br>n = process to n<br>TE = \frac{VAT}{TT} <br>VAT = \sum_{i=1}^{n} (VAT_i)<br>NVAT = \sum_{i=1}^{n} (NVAT_i)<br>TT = VAT + NVAT | Vinodh et al. (2014) |
| 5 | Energy (kWh) | EE = Efisiensi energi<br>VAE = energi pada kegiatan yang memiliki nilai tambah<br>NVAE = energi pada kegiatan yang tidak memiliki nilai tambah<br>ET = energi total<br>n = process to n<br>EE = \frac{VAE}{ET} <br>VAE = \sum_{i=1}^{n} (VAE_i)<br>NVAE = \sum_{i=1}^{n} (NVAE_i)<br>ET = VAE + NVAE | Vinodh et al. (2014) |
| 6 | Material (kg) | ME = Material efficiency<br>VAM = material on activities that have added value<br>TM = total material used<br>NVAM = material on activities that do not have added value<br>n = process to n<br>ME = \frac{VAM}{TM} <br>VAM = \sum_{i=1}^{n} (VAMI)<br>NVAM = \sum_{i=1}^{n} (NVAMI)<br>TM = VAM + NVAM | Vinodh et al. (2014) |
| 7 | Waste Recycle (kg) | WE = Waste efficiency<br>WL = Amount of land waste<br>WE = 1 - \frac{(WL)}{TM} | Helleno et al. (2017) |
| No. (i) | Indicators       | Input                                      | Formula          | References                                      |
|--------|------------------|--------------------------------------------|------------------|------------------------------------------------|
| 8      | Employee training| $E_{HRD} = \text{Employee training level}$ | $E_{HRD} = \frac{NT}{NE}$ | Hartini, Ciptomulyono, Anityasari et al. (2020) |
|        |                  | $NT = \text{Number of employees who attended the training}$ |                  |                                                |
|        |                  | $NE = \text{Total number of employees}$    |                  |                                                |
| 9      | Safety level     | $NR = \text{Number of activities at risk}$ | $RE = 1 - \left( \frac{NR}{Nac} \right)$ | Helleno et al. (2017)                          |
|        |                  | $Nac = \text{Total activity}$              |                  |                                                |
| 10     | Health level     | $NA = \text{Number of absent employees}$   | $HE = 1 - \left( \frac{NA}{NE} \right)$ | Helleno et al. (2017); Paju et al. (2010)     |
|        |                  | $NE = \text{total number of employees}$    |                  |                                                |
| 11     | Satisfaction level| $TO = \text{number of employee turnover}$  | $SE = 1 - \left( \frac{TO}{NE} \right)$ | Tett and Meyer (1993)                          |
|        |                  | $NE = \text{total number of employees}$    |                  |                                                |
from scores (1) Very irrelevant, (2) Irrelevant, (3) Neutral, (4) Relevant, and (5) Very relevant.

\[
WA = \frac{\sum SR_j}{Nr}
\]

(1)

\[
LC = \frac{FNR}{Nr}
\]

(2)

### 3.3. Interrelation indicator and indicator weighting

Multi-criteria decision-making is widely used in supply chain decision-making (Bag et al., 2021; A. K. Sahu et al., 2018; A. K., 2022), assessment logistics service (N. K. N. K. Sahu et al., 2015), and digital manufacturing barriers (Bag et al., 2022). In this research, multi-criteria decision-making is applied to assess interrelation indicators and indicator weighting. Dematel and ANP were proposed in this section to evaluate interrelation indicators and indicator weighting. Dematel is proposed to determine the relationship criterion. The ANP method is then used to determine the indicator TBL’s weighting. Using the Dematel method, the relationship between indicator can be evaluated. This procedure is based on Ranjbar et al. (2014) procedure. Using a scale of 0 (does not affect) to 4 (strongly affects), the Focus Group Discussion (FGD) team assesses the relationship between indicator. Results of the questionnaire are shown in a direct matrix (B) as shown in Equation (3). As a result, it is normalized using Equations (4) and (5), which produces a normalized matrix (X) where \( s \) represents the normalization constant and \( n \) describes the number of indicator. The normalization results are also used to calculate the total relation matrix (T) based on Equation (6). For the determination of \( Di \) and \( Rj \), Equations (7) and (8) must be used in their entirety. The total T-row and total T-column are represented by \( Di \) and \( Rj \), respectively. The prominence vector (\( Di + Rj \)) and the vector relation (\( Di - Rj \)) are obtained by using \( Di \) and \( Rj \). The Impact Relation Map (IRM) and threshold value are determined at this point in Dematel’s procedure. In order to determine whether one set of indicator is related to another, we use a value called the threshold (\( a \)). To determine whether the indicator are related, one must look at the T matrix’s value. The IRM, which serves as a network in the ANP procedure. Equation (9) shows an example of IRM on a T-matrices.

\[
B = \begin{bmatrix}
b_{11} & b_{1j} & b_{1n} \\
b_{i1} & b_{ij} & b_{in} \\
b_{n1} & b_{nj} & b_{nn}
\end{bmatrix}
\]

(3)

\[
s = \frac{1}{\max \sum_{j=1}^{n} b_{ij}}
\]

(4)

\[
X = sxB
\]

(5)

\[
T = X(I - X)^{-1}
\]

(6)
In this research, the ANP procedure is used to calculate a weighting indicator based on interrelation. The ANP method is based on Saaty (Saaty, 2004) and Yang et al. (2008). Pairwise comparisons on a scale of 1 (equal importance) to 9 (absolutely more important) are used to evaluate IRM results on Dematel. Equation (10) displays formula the unweighted supermatrix from the pairwise comparison assessment indicator (A). In addition, the weighted supermatrix is calculated in the next step. Transforming the initial T matrix to the a new matrix α-cut total relation matrix (Tα) is an important step in the analysis process. Equation (11) shows the Tα matrix, which is created by assigning a value of 0 to any matrix value less than the threshold value. It equations are used to calculate the weighted supermatrix (Aw) in Equations (12), (13), and (14). Where, di is the number of rows in the matrix T. The calculation of the Limiting supermatrix, which is formulated in Equation (15), is the final step in the ANP procedure. The weight of each TBL indicator is the result of the Limiting supermatrix.

\[
D_i = \left[ \sum_{j=1}^{n} t_{ij} \right]_{nx1}^{n} \\
R_j = \left[ \sum_{i=1}^{n} t_{ij} \right]_{1xn}^{n}
\]

\[
T = \begin{bmatrix}
t_{11} & t_{12} & t_{13} \\
t_{21} & t_{22} & t_{23} \\
t_{31} & t_{32} & t_{33}
\end{bmatrix}
\]

\[
T_{s} = \begin{bmatrix}
t_{i1}^{s}/d_{1} & t_{ij}^{s}/d_{1} & t_{1n}^{s}/d_{1} \\
t_{i1}^{s}/d_{i} & t_{ij}^{s}/d_{i} & t_{in}^{s}/d_{i} \\
t_{i1}^{s}/d_{3} & t_{ij}^{s}/d_{3} & t_{nn}^{s}/d_{3}
\end{bmatrix}
\]

\[
T_{s} = \begin{bmatrix}
t_{11}^{s} & t_{ij}^{s} & t_{1n}^{s} \\
t_{1i}^{s} & t_{ij}^{s} & t_{in}^{s} \\
t_{ni}^{s} & t_{nj}^{s} & t_{nn}^{s}
\end{bmatrix}
\]
\[ AW = \begin{bmatrix} t_{11}^1 x_{a11} & t_{12}^1 x_{a12} & \cdots & t_{1n}^1 x_{an1} \\ t_{21}^2 x_{a12} & t_{22}^2 x_{a22} & \cdots & t_{2n}^2 x_{an2} \\ t_{m1}^m x_{an1} & t_{m2}^m x_{an2} & \cdots & t_{mn}^m x_{ann} \end{bmatrix} \] (14)

\[ \lim_{k \to \infty} W^k_w \] (15)

### 3.4. Indicator efficiency assessment and sustainable VSM mapping

This section describes the mapping of indicators using Sustainable VSM. The Sustainable VSM is a classic VSM combined with a TBL indicator. It is expected to be able to describe the company’s performance using economic, environmental, and social aspects (Faulkner & Badurdeen, 2014). As described in the previous section, the relevant indicators were selected based on the Delphi method. Furthermore, the selected indicators are calculated for efficiency based on the formula presented in Table 3. The efficiency values for each indicator are used for mapping sustainable VSM. The efficiency values for each indicator in sustainable VSM are classified using the Traffic Light System (TLS) principle. Three colors are used for indicator mapping, namely red with a percentage of indicator value < 60%, indicating the indicator score is still below the target. The yellow color represents indicators with a 60%-90% indicating the achieved score needs improvement. The green color represents the percentage of indicators > 90%, indicating an excellent indicator (Hartini, Ciptomulyono, Anityasari et al., 2020). Furthermore, the efficiency value of each indicator is used to calculate the Manufacturing Sustainability Score (MSS), which is described in the following subsection.

### 3.5. Score manufacturing sustainability assessment

In this section, the MSS is based on the value of the efficiency of the indicator and the weight of the indicator. The MSS value is generated by multiplying the efficiency of the indicator with the weight of the indicator (Huang & Badurdeen, 2018; De Silva et al., 2009). The MSS calculation formula can be seen in equation (16). Where, \( W_i \) shows the weight of the \( i \)-indicator generated by the ANP method, and \( E_i \) shows the \( i \)-indicator efficiency score. The number of relevant indicators is denoted as \( n \).

\[ MSS = \sum_{i=1}^{n} W_i \cdot E_i \] (16)

MSS scores are also classified using the TLS principle, which is also used to classify efficiency indicators. The MSS percentage of 60% is shown in red, indicating that the score is still below the target. The percentage of 60% – 90% indicates that the indicator needs to be improved (which is depicted in yellow). Furthermore, an MSS percentage greater than 90% indicates that the indicator is on target (depicted in green).

### 4. Case study application

A case study was conducted in the wood furniture industry in Indonesia, which is of the make-to-order type. This study involved ten experts in assessing the relevant TBL
indicators. Each expert assessed the relevance score of the indicators used. Furthermore, the Delphi method uses the assessment score data to select relevant indicators according to the problems in the company. The results of the assessment of the relevance of each indicator are shown in Table 4. It shows two irrelevant indicators, namely the inventory indicator and the material consumption indicator. These results indicated that nine relevant indicators are used to assess manufacturing sustainability.

The experts also conducted a Focus Group Discussion (FGD) to assess the relationship between the indicators. The results of the assessment of the relationship between indicators are presented in Table 5. It used the Dematel method to assess the relationship between indicators of the TBL variables. The results of the α-cut total relation matrix are shown in Table 6 with a threshold value of 0.430. It shows that time and quality indicators are the most dispatcher indicators, followed by cost and energy indicators. In addition, the safety level is the most receiver indicator influenced by other indicators, followed by the health level. The α-cut total relation matrix is also used to describe the network in ANP. The ANP network in this problem is depicted in Figure 2. This study proposes three main clusters of the ANP network. Cluster 1 shows the comparison between indicators and aspects of TBL. Next, a comparison of each aspect of TBL is presented in cluster 2. Finally, cluster 3 is a pairwise comparison between TBL indicators. Super decision software was used as a tool to carry out ANP procedures.

FGD data for pairwise comparison assessment between indicators and aspects of TBL is presented in Table A1-A12 in Appendix A. Data for each indicator is collected from 6

| Table 4. Results of the assessment of the relevance of each indicator. |
|---------------------------------------------------------------|
| **Factors** | **Indicators** | **Relevance** | **1** | **2** | **3** | **4** | **5** | **WA** | **LC** |
|---------------------------------------------------------------|
| Economic | Time | 4 | 6 | 4.6 | 1 | | | | |
| | Inventory | 3 | 4 | 2 | 1 | 3.1 | 0.3 | | | |
| | Quality | 3 | 7 | 4.7 | 1 | | | | | |
| | Cost | 10 | 5 | 1 | | | | | | |
| Enviroment | Material | 3 | 3 | 2 | 2 | 3.3 | 0.4 | | | |
| | Energy | 2 | 5 | 3 | 4.1 | 0.8 | | | | |
| | Waste recycle | 1 | 9 | 4.9 | 1 | | | | | |
| Social | Satisfaction level | 10 | 5 | 1 | | | | | | |
| | Health level | 10 | 5 | 1 | | | | | | |
| | Safety level | 1 | 9 | 4.9 | 1 | | | | | |
| | Employee training | 2 | 3 | 5 | 4.3 | 0.8 | | | | |

Table 5. Assessment of the relationship between indicators.

| Indicators | Time | Quality | Cost | Energy | Waste recycle | Satisfaction level | Health level | Safety level | Employee training |
|------------|------|---------|------|--------|---------------|--------------------|--------------|--------------|------------------|
| Time       | 0    | 4       | 4    | 3      | 2             | 1                  | 1            | 1            | 3                |
| Quality    | 4    | 0       | 3    | 3      | 4             | 4                  | 0            | 0            | 1                |
| Cost       | 2    | 3       | 0    | 2      | 1             | 3                  | 1            | 1            | 2                |
| Energy     | 3    | 3       | 3    | 0      | 1             | 1                  | 0            | 0            | 0                |
| Waste recycle | 3 | 4       | 4    | 2      | 0             | 0                  | 3            | 1            | 3                |
| Satisfaction level | 4 | 3       | 3    | 2      | 3             | 0                  | 2            | 3            | 2                |
| Health level | 4    | 4       | 4    | 2      | 2             | 4                  | 0            | 3            | 1                |
| Safety level | 3    | 3       | 3    | 2      | 3             | 3                  | 3            | 0            | 3                |
| Employee training | 4 | 4       | 3    | 3      | 4             | 1                  | 1            | 4            | 0                |
work stations, including measurement, cutting, planer, router trimmer, assembly, and finishing. The components of the data collected on each indicator are presented in Table 3. Furthermore, these are used for calculating efficiency and manufacturing sustainability scores.

5. Results and discussion

5.1. Assessment results

The results of the weighting of indicators using ANP are presented in Table 7. The index value of the consistency ratio of the pairwise comparisons is below 10%, which indicates that the data is consistent. This study shows that quality has a high weight, followed by time and cost indicators. Quality is the most critical indicator of manufacturing sustainability because it satisfies customers. This study’s results align with research conducted by Hartini, Ciptomulyono, Anityasari et al. (2020). Based on the research by Saidani and Arifin (2012), product quality can influence consumer satisfaction and buying interest.
Therefore, the company must make a product quality plan oriented to product quality, which will be an advantage that can be used to face the competition (Iswanto et al., 2013).

In addition, the time indicator is the most important because the waste of time that is not added value can reduce the company’s performance. This indicator also has the effect of decreasing the performance of the cost indicator. Cost also has a critical role in achieving sustainable development. Cost is the equivalent value sacrificed to get a product that is expected to be helpful in the present and future. The costs in the production process include the cost of raw materials, labor costs, and factory overhead (Vinodh et al., 2014). The cost indicator in the company is used as a measure of the success of a business.

The results of the calculation of the efficiency of each indicator and MSS are shown in Table 8. Furthermore, the mapping of sustainable VSM is depicted in Figure 3. These results show that the time, quality, cost, and energy indicators contribute to the highest indicator score. Based on the Sus-VSM and TLS mapping results, eight indicators have moderate (yellow) and low (red) efficiency values. In the time indicator, three work stations have low-efficiency values: cutting (43.5%), router trimmer (53.9%), and finishing (43.8%). The trimmer router workstation has the lowest quality indicator efficiency (0.7%). The waste recycling and employee training indicators have an efficiency value of 0%. The health level indicator contributes 46% efficiency, and the Safety level indicator has 50% efficiency. The MSS in this industry is 66.97%, which shows that the performance of manufacturing sustainability in the production line is still lacking.

| Factors   | Indicators               | Efficiency (%) | Weight | Score indicators | MSS  |
|-----------|--------------------------|----------------|--------|------------------|------|
| Economic  | Time                     | 63.6           | 0.260  | 16.56            | 66.97% |
|           | Quality                  | 85.2           | 0.285  | 24.31            |      |
|           | Cost                     | 99.3           | 0.130  | 12.87            |      |
| Environment| Energy                   | 100            | 0.104  | 10.37            |      |
|           | Waste recycling          | 0              | 0.150  | 0.00             |      |
| Social    | Satisfaction level       | 62             | 0.010  | 0.62             |      |
|           | Health level             | 46             | 0.023  | 1.07             |      |
|           | Safety level             | 50             | 0.023  | 1.17             |      |
|           | Employee training        | 0              | 0.015  | 0.00             |      |

Table 7. Weight indicators based on ANP.

Table 8. Calculation Results of Indicator and Manufacturing Sustainability Score.
5.2. Practical and managerial implications

This study contains several managerial insights that are not only academic but also managerial. The implications of each point of view are clearly explained below.

5.2.1. Academic implications

Manufacturing companies can better assess, map, and improve operations using this method to achieve manufacturing sustainability. This proposed method is intended to fill gaps in previous research that has extensively used the TBL concept but falls short in analyzing the interaction between indicators. Using this method, the decision-maker can explain the significance of the interrelation of each indicator TBL. The production line is a manufacturing system component, contributing to economic, social, and environmental issues. With this understanding, it is clear that the environment, economy, and society all play important roles in long-term development and interact with one another. The interaction of indicators influences the weight of importance, influencing the manufacturing sustainability score.

According to the study, inefficient production lines in terms of TBL impact the manufacturing sustainability score. As a result of this research, academic research in other industrial sectors needs further improvement and investigation. Previous studies on sustainable manufacturing practices have not been thoroughly investigated, but they are a promising beginning.

5.2.2. Managerial implications and recommendations

This study assists industry managers in focusing on sustainable manufacturing practices to increase their chances of implementing sustainable manufacturing. Managers are
encouraged to make the best decisions possible to improve the manufacturing sustainability score in today’s increasingly complex business environment.

According to the research findings, six indicators have low-efficiency values: waste recycling, employee training, health level, safety level, time, and quality. On the other hand, the energy indicator has high efficiency in this industry (Utama, 2022; Utama & Widodo, 2021). It demonstrates that the company has implemented an efficient manufacturing process. Scheduling correctly has improved energy efficiency in the manufacturing process (Utama, Widodo, Ibrahim, Hidayat et al., 2020; Utama et al., 2019). The following are recommendations for improving performance in each indicator:

(a) Recommendations for improving waste recycling indicators’ performance include collaborating with third parties for waste management. For example, the industry can use wood waste to make fertilizers and handicrafts.
(b) Recommendations for improving employee training indicators include training to increase worker skills in making a product in particular and in the use of machines. Defects in a part or unit due to a lack of skills can affect production time and costs.
(c) The proposed improvement for the health level indicator is to apply work discipline and follow up on wood assault waste to minimize employee health problems.
(d) Proposed enhancements to safety level indicators, namely increased worker discipline in using personal protective equipment. Many workers who do not use personal protective equipment are discovered, causing the impact felt by workers and businesses. The company may incur losses in terms of both time and money.
(e) Proposed value-add improvements, such as eliminating non-value-added activities such as waiting. Furthermore, businesses must implement 5S, inspect each workstation, and develop standard operational procedures.
(f) Finally, the quality indicator recommendation is to conduct inspections at each work station to detect defects before the product reaches the consumer.

6. Conclusion

The primary goal of this research is to develop a new Manufacturing Sustainability Performance Assessment (MSPA) framework for the manufacturing process line. In the manufacturing process line, a new framework with a hybrid method has been successfully developed for MSPA. The Delphi method was used to choose relevant indicators. Relevant indicators are calculated for efficiency and mapped into sustainable VSM and TLS. The MSS calculation is based on the weight of the Dematel-ANP method indicators and the efficiency of each indicator. This proposed framework is also used in the Indonesian furniture industry. The case study results show that the furniture industry’s manufacturing sustainability performance needs improvement (yellow). Furthermore, it demonstrates that the proposed method can be used to solve real-world problems.

This study makes two significant contributions to the MSPA. First, as a novel contribution, we propose a new MSPA framework for use in sustainable manufacturing firms. The proposed framework incorporates Delphi-Dematel-ANP and long-term VSM procedures. The second contribution is that we empirically tested the proposed framework in industrial furniture manufacturing companies. It is done because no MSPA assessment includes interrelationship indicators.
As with previous studies, the limitations of the research presented in this paragraph also apply to this study. First, our study focuses on manufacturing companies that produce a product variant, whereas the current MSPA assessment focuses on a single product. Second, this study is based on data collected over a specific time horizon and with deterministic data types. This problem assumes that the information obtained is clear. Third, we have not included worker mental and physical workload indicators that were not considered in the MSPA. Our framework will be complete if we include workers’ mental and physical workload indicators. Fourth, this case study only assesses the feasibility of the proposed model for evaluating MSPA, particularly in the furniture industry. It should be noted that the indicators used in this study are only relevant for evaluating industries that are part of the furniture sector. Finally, the current framework should be investigated further under different conditions, which may provide different insights into the current framework. The following is a description of the future research direction:

- More research is needed to consider multiple product variants in the MSPA assessment so that the new framework can evaluate manufacturing firms producing multiple products.
- In order to represent uncertainty, MSPA must consider fuzzy and stochastic data types.
- In order to fully assess manufacturing’s sustainability performance, additional research must consider worker mental and physical workload indicators.
- Additional research on various manufacturing industries is required to validate the model and improve the indicators in the proposed framework.

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Data availability

All data generated or analyzed during this study are included in this article.
References

Atieh, A. M., Kayhani, H., Almuhtady, A., & Al-Tamimi, O. (2016). A value stream mapping and simulation hybrid approach: Application to glass industry. The International Journal of Advanced Manufacturing Technology, 84(5–8), 1573–1586. https://doi.org/10.1007/s00170-015-7805-8

Azevedo, S. G., & Barros, M. (2017). The application of the triple bottom line approach to sustainability assessment: The case study of the UK automotive supply chain. Journal of Industrial Engineering and Management (JIEM), 10(2), 286–322. https://doi.org/10.3926/jiem.1996

Bag, S., Sahu, A. K., Kilbourn, P., Pisa, N., Dhamija, P., & Sahu, A. K. (2022). Modeling barriers of digital manufacturing in a circular economy for enhancing sustainability. International Journal of Productivity and Performance Management, 71(3), 833–869. https://doi.org/10.1108/IJPPM-12-2020-0637

Bag, S., Viktorovich, D. A., Sahu, A. K., & Sahu, A. K. (2021). Barriers to adoption of blockchain technology in green supply chain management. Journal of Global Operations and Strategic Sourcing, 14(1), 104–133. https://doi.org/10.1108/JG OSS-06-2020-0027

Bait, S., Di Pietro, A., & Schiraldi, M. M. (2020). Waste Reduction in Production Processes through Simulation and VSM. Sustainability, 12(8), 3291. https://doi.org/10.3390/su12083291

Bhada, J., Kumar, P., Bhamu, J., & Singh, D. (2022). Lean production performance indicators for medium and small manufacturing enterprises: Modelling through analytical hierarchy process. International Journal of System Assurance Engineering and Management, 13(2), 978–997. https://doi.org/10.1007/s13198-021-01375-6

Brown, A., Amundson, J., & Badurdeen, F. (2014). Sustainable value stream mapping (Sus-VSM) in different manufacturing system configurations: Application case studies. Journal of Cleaner Production, 85, 164–179. https://doi.org/10.1016/j.jclepro.2014.05.101

Castiglione, C., Pastore, E., & Alfieri, A. (2022). Technical, economic, and environmental performance assessment of manufacturing systems: The multi-layer enterprise input-output formalization method. Production Planning & Control, 1–18. https://doi.org/10.1080/09537287.2022.2054743

Cherier, M. A., & Meliani, S. M. (2019). Supplier selection on agrifood supply chain: A Delphi-AHP-TOPSIS methodology. International Journal of Knowledge Engineering and Data Mining, 6(4), 307–330. https://doi.org/10.1504/IJKEDM.2019.105244

Cherrafi, A., Elfezazi, S., Chiarini, A., Mokhli, A., & Benhida, K. (2016). The integration of lean manufacturing, Six Sigma and sustainability: A literature review and future research directions for developing a specific model. Journal of Cleaner Production, 139, 828–846. https://doi.org/10.1016/j.jclepro.2016.08.101

De Silva, N., Jawahir, I., Dillon, J. O., & Russell, M. (2009). A new comprehensive methodology for the evaluation of product sustainability at the design and development stage of consumer electronic products. International Journal of Sustainable Manufacturing, 1(3), 251–264. https://doi.org/10.1504/IJSM.2009.023973

Dewi, S. K., Utama, D. M., & Rohman, R. N. (2021 15-16 July 2020). Minimize waste on production process using lean concept. In Mujiarto (Ed.), The 1st Paris Van Java International Seminar on Computer, Science, Engineering, and Technology (PVJ_ISComSET) (pp. 1-7). IOP Publishing

Elkington, J. (1998). Partnerships from cannibals with forks: The triple bottom line of 21st-century business. Environmental Quality Management, 8(1), 37–51. https://doi.org/10.1002/tqem.3310080106

Faulkner, W., & Badurdeen, F. (2014). Sustainable Value Stream Mapping (Sus-VSM): Methodology to visualize and assess manufacturing sustainability performance. Journal of Cleaner Production, 85, 8–18. https://doi.org/10.1016/j.jclepro.2014.05.042

Faulkner, W., Templeton, W., Gullett, D., & Badurdeen, F. (2012). Visualizing sustainability performance of manufacturing systems using sustainable value stream mapping (Sus-VSM). (Ed.), (Eds.). The 2012 international conference on industrial engineering and operations management, Istanbul, Turkey: ieom society.
Fearne, A., & Norton, A. (2006). Sustainable value stream mapping: A tool for process change and waste reduction. European Federation of Food Science and Technology.

Feil, A. A., de Quevedo, D. M., & Schreiber, D. (2015). Selection and identification of the indicators for quickly measuring sustainability in micro and small furniture industries. Sustainable Production and Consumption, 3, 34–44. https://doi.org/10.1016/j.spc.2015.08.006

Garza-Reyes, J. A., Kumar, V., Chaikittisilp, S., & Tan, K. H. (2018). The effect of lean methods and tools on the environmental performance of manufacturing organisations. International Journal of Production Economics, 200, 170–180. https://doi.org/10.1016/j.ijpe.2018.03.030

Garza-Reyes, J. A., Romero, J. T., Govindan, K., Cherrafi, A., & Ramanathan, U. (2018). A PDCA-based approach to environmental value stream mapping (E-VSM). Journal of Cleaner Production, 180, 335–348. https://doi.org/10.1016/j.jclepro.2018.01.121

Hartini, S., Ciptomulyono, U., & Anityasari, M. (2017a). Extended value stream mapping to enhance sustainability: A literature review. (Ed.), (Eds.). AIP Conference Proceedings.

Hartini, S., Ciptomulyono, U., & Anityasari, M. (2017b). Extended value stream mapping to enhance sustainability: A literature review. AIP Conference Proceedings, 1902(1), 020030. https://doi.org/10.1063/1.5010647

Hartini, S., Ciptomulyono, U., & Anityasari, M. (2020). Manufacturing sustainability assessment using a lean manufacturing tool. International Journal of Lean Six Sigma, 11(5), 943–971. https://doi.org/10.1108/IJLSS-12-2017-0150

Hartini, S., Ciptomulyono, U., Anityasari, M., & Sriyanto, S. (2020). Manufacturing sustainability assessment using a lean manufacturing tool. International Journal of Lean Six Sigma, 11(5), 943–971. https://doi.org/10.1108/IJLSS-12-2017-0150

Hartini, S., Manurung, J., & Rumita, R. (2021). Sustainable-value stream mapping to improve manufacturing sustainability performance: Case study in a natural dye batik SME’s. IOP Conference Series: Materials Science and Engineering, 1072(1), 012066. https://doi.org/10.1088/1757-899x/1072/1/012066

Helleeno, A. L., de Moraes, A. J. I., & Simon, A. T. (2017). Integrating sustainability indicators and Lean Manufacturing to assess manufacturing processes: Application case studies in Brazilian industry. Journal of Cleaner Production, 153, 405–416. https://doi.org/10.1016/j.jclepro.2016.12.072

Huang, A., & Badurdeen, F. (2018). Metrics-based approach to evaluate sustainable manufacturing performance at the production line and plant levels. Journal of Cleaner Production, 192, 462–476. https://doi.org/10.1016/j.jclepro.2018.04.234

Ibrahim, M. F., Putri, M. M., & Utama, D. M. (2020, 23–24 October 2019). A literature review on reducing carbon emission from supply chain system: Drivers, barriers, performance indicators, and practices. (Ed.), (Eds.). 3rd International Conference on Engineering Technology for Sustainable Development (ICET4SD) Yogyakarta, Indonesia: IOP Publishing.

Iswanto, A., Rambe, M., Jabbar, A., & Ginting, E. (2013). Aplikasi metodologi Taguchi Analysis dalam failure mode and effect analysis (fmea) untuk perbaikan kualitas produk di PT. XYZ. Jurnal Teknik Industri USU, 2(2), 219330. https://jurnal.usu.ac.id/index.php/jti/article/view/3706

Jiang, P., Hu, Y. C., Yen, G. F., & Tsao, S. J. (2018). Green supplier selection for sustainable development of the automotive industry using grey decision-making. Sustainable Development, 26(6), 890–903. https://doi.org/10.1002/sd.1860

Lee, J. K. Y., Gholami, H., Saman, M. Z. M., Ngadiman, N. H. A. B., Zakuan, N., Mahmood, S., & Omain, S. Z. (2021). Sustainability-oriented application of value stream mapping: A review and classification. IEEE Access, 9, 68414–68434. https://doi.org/10.1109/ACCESS.2021.3077570

Lee, J. Y., Kang, H. S., & Noh, S. D. (2014). MAS2: An integrated modeling and simulation-based life cycle evaluation approach for sustainable manufacturing. Journal of Cleaner Production, 66, 146–163. https://doi.org/10.1016/j.jclepro.2013.11.029

Leksono, E. B., Suparno, S., & Vanany, I. (2019). Integration of a balanced scorecard, DEMATEL, and ANP for measuring the performance of a sustainable healthcare supply chain. Sustainability, 11(13), 3626. https://doi.org/10.3390/su11133626

Liu, X., Deng, Q., Gong, G., Zhao, X., & Li, K. (2021). Evaluating the interactions of multi-dimensional value for sustainable product-service system with grey DEMATEL-ANP
approach. *Journal of Manufacturing Systems*, 60, 449–458. https://doi.org/10.1016/j.jmsy.2021.07.006

Machado, C. G., Winroth, M. P., & Ribeiro da Silva, E. H. D. (2020). Sustainable manufacturing in Industry 4.0: An emerging research agenda. *International Journal of Production Research*, 58(5), 1462–1484. https://doi.org/10.1080/00207543.2019.1652777

Miller, G. (2001). The development of indicators for sustainable tourism: Results of a Delphi survey of tourism researchers. *Tourism Management*, 22(4), 351–362. https://doi.org/10.1016/S0261-5177(00)00067-4

Mishra, A. K., Sharma, A., Sachdeo, M., & K, J. (2020). Development of sustainable value stream mapping (SVSM) for unit part manufacturing. *International Journal of Lean Six Sigma*, 11(3), 493–514. https://doi.org/10.1108/IJLSS-04-2018-0036

Mohammad Ebrahimi, S., & Koh, L. (2021). Manufacturing sustainability: Institutional theory and life cycle thinking. *Journal of Cleaner Production*, 298, 126787. https://doi.org/10.1016/j.jclepro.2021.126787

Moldavska, A., & Welo, T. J. O. M. S. (2019). A Holistic approach to corporate sustainability assessment: Incorporating sustainable development goals into sustainable manufacturing performance evaluation. 50, 53–68. https://doi.org/10.1016/j.jmsy.2018.11.004

Noly, N. R. (2018). Analisis critical success factor terhadap kesuksesan implementasi open ERP Odoo Dengan Metode Delphi. Institut Teknologi Sepuluh Nopember.

Ocampo, L., Deiparine, C. B., & Go, A. L. (2020). Mapping strategy to best practices for sustainable food manufacturing using fuzzy DEMATEL-ANP-TOPSIS. *Engineering Management Journal*, 32(2), 130–150. https://doi.org/10.1080/10429247.2020.1733379

Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool: An example, design considerations and applications. *Information & Management*, 42(1), 15–29. https://doi.org/10.1016/j.im.2003.11.002

Paju, M., Heilala, J., Hentula, M., Heikkilä, A., Johansson, B., Leong, S., & Lyons, K. (2010). Framework and indicators for a sustainable manufacturing mapping methodology. (Ed.), (Eds.). *Proceedings of the 2010 winter simulation conference*.

Patalas-Maliszewska, J., Łosyk, H., & Rehm, M. (2022). Decision-tree based methodology aid in assessing the sustainable development of a manufacturing company. *Sustainability*, 14(10), 6362. https://doi.org/10.3390/su14106362

Pusavec, F., Krajnik, P., & Kopac, J. (2010). Transitioning to sustainable production – Part I: Application on machining technologies. *Journal of Cleaner Production*, 18(2), 174–184. https://doi.org/10.1016/j.jclepro.2009.08.010

Quezada, L. E., López-Ospina, H. A., Palominos, P. I., & Oddershede, A. M. (2018). Identifying causal relationships in strategy maps using ANP and DEMATEL. *Computers & Industrial Engineering*, 118, 170–179. https://doi.org/10.1016/j.cie.2018.02.020

Ranjarb, M. S., Shirazi, M. A., & Blooki, M. L. (2014). Interaction among intra-organizational factors effective in successful strategy execution: An analytical view. *Journal of Strategy and Management*, 7(2), 124–154. https://doi.org/10.1108/JSMA-05-2013-0032

Rao, S.-H. (2021). A hybrid MCDM model based on DEMATEL and ANP for improving the measurement of corporate sustainability indicators: A study of Taiwan High Speed Rail. *Research in Transportation Business & Management*, 41, 100657. https://doi.org/10.1016/j. rtbm.2021.100657

Rogers, K., & Hudson, B. (2011). The triple bottom line. *OD Practitioner*, 43(4), 4.

Rowe, G., & Wright, G. (1999). The Delphi technique as a forecasting tool: Issues and analysis. *International Journal of Forecasting*, 15(4), 353–375. https://doi.org/10.1016/S0169-2070(99)00018-7

Saaty, T. L. (2004). Decision making—the analytic hierarchy and network processes (AHP/ANP). *Journal of Systems Science and Systems Engineering*, 13(1), 1–35. https://doi.org/10.1007/s11518-006-0151-5

Saavalainen, P., Turpeinen, E., Omodara, L., Kabra, S., Oraviskärvi, K., Yadav, G. D., Keiski, R. L., & Pongrácz, E. (2017). Developing and testing a tool for sustainability assessment in an early process design phase—Case study of formic acid production by conventional and carbon
Sahu, A. K., Naval, D., Narang, H. K., & Rajput, M. S. (2018). A merged approach for modeling qualitative characteristics of agile arena under grey domain. *Grey Systems: Theory and Application, 8*(3), 328–357. https://doi.org/10.1108/GS-03-2018-0013

Sahu, N. K., Sahu, A. K., & Sahu, A. K. (2015). Appraisal and benchmarking of third-party logistic service provider by exploration of risk-based approach. *Cogent Business & Management, 2*(1), 1121637. https://doi.org/10.1080/23311975.2015.1121637

Sahu, A. K., Sharma, M., Raut, R. D., Sahu, A. K., Sahu, N. K., Antony, J., & Tortorella, G. L. (2022). Decision-making framework for supplier selection using an integrated MCDM approach in a lean-agile-resilient-green environment: Evidence from Indian automotive sector. *The TQM Journal, ahead-of-print*(ahead-of-print). https://doi.org/10.1108/TQM-12-2021-0372

Saidani, B., & Arifin, S. (2012). Pengaruh kualitas produk dan kualitas layanan terhadap kepuasan konsumen dan minat beli pada ranch market. *JRMSI-Jurnal Riset Manajemen Sains Indonesia, 3*(1), 1–22. http://journal.unj.ac.id/unj/index.php/jrmsi/article/view/766

Schoeman, Y., Oberholster, P., & Somerset, V. (2021). Value stream mapping as a supporting management tool to identify the flow of industrial waste: A case study. *Sustainability, 13*(1). https://doi.org/10.3390/su13010091

Searcy, C. (2012). Corporate sustainability performance measurement systems: A review and research agenda. *Journal of Business Ethics, 107*(3), 239–253. https://doi.org/10.1007/s10551-011-1038-z

Simpson, D. (2012). Knowledge resources as a mediator of the relationship between recycling pressures and environmental performance. *Journal of Cleaner Production, 22*(1), 32–41. https://doi.org/10.1016/j.jclepro.2011.09.025

Soltani, M., Aouag, H., & Mouss, M. D. (2020). An integrated framework using VSM, AHP and TOPSIS for simplifying the sustainability improvement process in a complex manufacturing process. *Journal of Engineering, Design and Technology, 18*(1), 211–229. https://doi.org/10.1108/JEDT-09-2018-0166

Sparks, D. T. (2014). *Combining sustainable value stream mapping and simulation to assess manufacturing supply chain network performance.* Institute of Industrial Engineers-Publisher.

Sultan, F. A., Routroy, S., & Thakur, M. (2021). A simulation-based performance investigation of downstream operations in the Indian Surimi Supply Chain using environmental value stream mapping. *Journal of Cleaner Production, 286*, 125389. https://doi.org/10.1016/j.jclepro.2020.125389

Swarnakar, V., Singh, A. R., Antony, J., Jayaraman, R., Tiwari, A. K., Rathi, R., & Cudney, E. (2022). Prioritizing indicators for sustainability assessment in manufacturing process: An integrated approach. *Sustainability, 14*(6), 3264. https://doi.org/10.3390/su14063264

Swarnakar, V., Singh, A. R., Antony, J., Tiwari, A. K., & Cudney, E. (2021). Development of a conceptual method for sustainability assessment in manufacturing. *Computers & Industrial Engineering, 158*, 107403. https://doi.org/10.1016/j.cie.2021.107403

Tett, R. P., & Meyer, J. P. (1993). Job satisfaction, organizational commitment, turnover intention, and turnover: Path analyses based on meta-analytic findings. *Personnel Psychology, 46*(2), 259–293. https://doi.org/10.1111/j.1744-6570.1993.tb00874.x

Theng, L. M., Tan, J., Liew, P. Y., & Tan, L. S. (2021). A review of manufacturing sustainability assessment tool selection criteria: A quantitative score-rating system versus process-data sustainability assessment. *Chemical Engineering Transactions, 89*, 523–528. https://doi.org/10.33007/CET2189088

Torres, J. A. S., & Gati, A. M. (2009). Environmental value stream mapping (EVSM) as sustainability management tool. (Ed.), (Eds.). *PICMET’09-2009 Portland International Conference on Management of Engineering & Technology.*

Utama, D. M. (2022). An effective hybrid crow search algorithm for energy-efficient flow shop scheduling. *AIP Conference Proceedings, 2453*(1), 020040. https://doi.org/10.1063/5.0094254
Utama, D. M., Dewi, S. K., & Mawarti, V. I. (2016). Identifikasi waste pada proses produksi key set clarinet dengan pendekatan lean manufacturing. *Jurnal Ilmiah Teknik Industri, 15*(1), 36–46. https://doi.org/10.23917/jiti.v15i1.1572

Utama, D. M., Maharani, B., & Amallynda, I. (2021). Integration Dematel and ANP for The Supplier Selection in The Textile Industry: A Case Study. *Jurnal Ilmiah Teknik Industri, 20*(1), 119–130. https://doi.org/10.23917/jiti.v20i1.13806

Utama, D. M., Putri, A. A., & Amallynda, I. (2021). A Hybrid Model for Green Supplier Selection and Order Allocation: DEMATEL, ANP, and Multi-criteria Goal Programming Approach. *Jurnal Optimasi Sistem Industri, 20*(2), 147–155. https://doi.org/10.25077/josi.v20.n2.p147-155.2021

Utama, D. M., Widjonarko, B., & Widodo, D. S. (2022). A novel hybrid jellyfish algorithm for minimizing fuel consumption capacitated vehicle routing problem. *Bulletin of Electrical Engineering and Informatics, 11*(3), 1272–1279. https://doi.org/10.11591/eei.v11i3.3263

Utama, D. M., & Widodo, D. S. (2021). An energy-efficient flow shop scheduling using hybrid Harris hawks optimization. *Bulletin of Electrical Engineering and Informatics, 10*(3), 1154–1163. https://doi.org/10.11591/eei.v10i3.2958

Utama, D. M., Widodo, D. S., Ibrahim, M. F., & Dewi, S. K. (2020). A new hybrid butterfly optimization algorithm for green vehicle routing problem. *Journal of Advanced Transportation, 2020*, 8834502. https://doi.org/10.1155/2020/8834502

Utama, D. M., Widodo, D. S., Ibrahim, M. F., Hidayat, K., Baroto, T., & Yurifah, A. (2020, 17–18 October 2019). The hybrid whale optimization algorithm: A new metaheuristic algorithm for energy-efficient on flow shop with dependent sequence setup. (Ed.), (Eds.). *International Conference on Science and Technology 2019 Surabaya, Indonesia: IOP Publishing.

Utama, D. M., Widodo, D. S., Wicaksono, W., & Ardiansyah, L. R. (2019). A new hybrid metaheuristics algorithm for minimizing energy consumption in the flow shop scheduling problem. *International Journal of Technology, 10*(2), 320–331. https://doi.org/10.14716/ijtech.v10i2.2194

Vinodh, S., Jayakrishna, K., Kumar, V., & Dutta, R. (2014). Development of decision support system for sustainability evaluation: A case study. *Clean Technologies and Environmental Policy, 16*(1), 163–174. https://doi.org/10.1007/s10098-013-0613-7

Widiasih, W., Karningsih, P. D., & Ciptomulyono, U. (2015). *Identifikasi Risiko pada saat implementasi lean manufacturing dengan metode Delphi*. (Ed.) Seminar Nasional MMT. Yang, Y.-P. O., Shieh, H.-M., Leu, J.-D., & Tzeng, G.-H. (2008). A novel hybrid MCDM model combined with DEMATEL and ANP with applications. *International Journal of Operations Research, 5*(3), 160–168. https://doi.org/10.7275/rrph-t210

Yousuf, M. I. (2007). Using experts’ opinions through Delphi technique. *Practical Assessment, Research, and Evaluation, 12*(1), 4.

Zhu, X.-Y., Zhang, H., & Jiang, Z.-G. (2020). Application of green-modified value stream mapping to integrate and implement lean and green practices: A case study. *International Journal of Computer Integrated Manufacturing, 33*(7), 716–731. https://doi.org/10.1080/0951192X.2019.1667028
Appendix A

Table A1. Pairwise comparisons between TBL factors.

|          | Economic | Environment | Social |
|----------|----------|-------------|--------|
| Economic | 1        | 2           | 3      |
| Environment | 1/2     | 1           | 2      |
| Social   | 1/3      | 1/2         | 1      |

Table A2. Pairwise comparison of indicators on economic factors.

|      | Cost | Quality | Time |
|------|------|---------|------|
| Cost | 1    | 1/2     | 1/2  |
| Quality | 2    | 1       | 1    |
| Time | 2    | 1       | 1    |

Table A3. Pairwise comparison of indicators on environmental factors.

|      | Energy | Waste |
|------|--------|-------|
| Energy | 1      | 1/2   |
| Waste | 2      | 1     |

Table A4. Pairwise comparison of indicators on social factors.

|       | Employee | Health | Safety | Satisfaction |
|-------|----------|--------|--------|--------------|
| Employee | 1        | 1/2    | 1/2    | 2            |
| Health  | 2        | 1      | 1      | 3            |
| Safety  | 2        | 1      | 1      | 3            |
| Satisfaction | 1/2 | 1/3 | 1/3 | 1         |

Table A5. Pairwise comparison of indicators that affect cost indicator.

|      | Quality | Time |
|------|---------|------|
| Quality | 1      | 2    |
| Time   | 1/2     | 1    |

Table A6. Pairwise comparison of indicators that affect Employee training indicators.

|     | Cost | Energy | Quality | Time | Waste |
|-----|------|--------|---------|------|-------|
| Cost | 1    | 1      | 1/2     | 1/2  | 2     |
| Energy | 1    | 1      | 1/2     | 1/2  | 2     |
| Quality | 2    | 2      | 1       | 1    | 2     |
| Time   | 2    | 2      | 1       | 1    | 2     |
| Waste  | 1/2  | 1/2    | 1/2     | 1/2  | 1     |
Table A7. Pairwise comparison of indicators that affect the indicator Health.

|     | Cost | Energy | Quality | Satisfaction | Time | Waste |
|-----|------|--------|---------|--------------|------|-------|
| Cost| 1    | 2      | 1/2     | 1            | 1/2  | 2     |
| Energy| 1/2  | 1      | 1/2     | 1/3          | 1    | 3     |
| Quality| 2    | 2      | 1       | 2            | 2    | 2     |
| Satisfaction| 1    | 1      | 1/2     | 1            | 1    | 2     |
| Time | 1    | 3      | 1/2     | 1            | 1    | 2     |
| Waste| 1/2  | 1/3    | 1/2     | 1/2          | 1/2  | 1     |

Table A8. Pairwise comparison of indicators that affect Quality indicators.

|     | Cost | Energy | Quality | Time | Waste |
|-----|------|--------|---------|------|-------|
| Cost| 1    | 2      | 1/2     | 1/2  | 2     |
| Energy| 1/2  | 1      | 1/3     | 1/3  | 1     |
| Quality| 2    | 3      | 1       | 1    | 2     |
| Time | 2    | 3      | 1       | 1    | 2     |
| Waste| 1/2  | 1      | 1/2     | 1/2  | 1     |

Table A9. Pairwise comparison of indicators that affect safety indicators.

|     | Cost   | Employee | Energy | Quality | Satisfaction | Time | Waste |
|-----|--------|----------|--------|---------|--------------|------|-------|
| Cost| 1      | 1/2      | 1/2    | 1/3     | 2            | 1    | 1     |
| Employee| 2     | 1        | 1      | 1/2     | 2            | 2    | 2     |
| Energy| 2      | 1        | 1      | 1/2     | 2            | 2    | 2     |
| Quality| 3     | 2        | 2      | 1       | 4            | 2    | 2     |
| Satisfaction| 1/2  | 1/2      | 1/2    | 1/4     | 1            | 1/2  | 1     |
| Time | 1     | 1/2      | 1/2    | 1/2     | 2            | 1    | 1     |

Table A10. Pairwise comparison of indicators that affect the Satisfaction indicator.

|     | Cost  | Energy | Quality | Time | Waste |
|-----|-------|--------|---------|------|-------|
| Cost| 1     | 1/2    | 1/2     | 1/2  | 2     |
| Energy| 2    | 1      | 1       | 1    | 2     |
| Quality| 2     | 1      | 1       | 1    | 2     |
| Time | 2     | 1      | 1       | 1    | 2     |
| Waste| 1/2   | 1/2    | 1/2     | 1/2  | 1     |

Table A11. Pairwise comparison of indicators that affect Time indicators.

|     | Cost | Energy | Quality | Time |
|-----|------|--------|---------|------|
| Cost| 1    | 3      | 1/2     | 1/2  |
| Energy| 1/3  | 1      | 1/4     | 1/4  |
| Quality| 2    | 4      | 1       | 1    |
| Time | 2    | 4      | 1       | 1    |

Table A12. Pairwise comparison of indicators that affect Waste Recycle indicators.

|     | Cost | Energy | Quality | Time |
|-----|------|--------|---------|------|
| Cost| 1    | 2      | 1/2     | 1/2  |
| Energy| 1/2  | 1      | 1/3     | 1/3  |
| Quality| 2     | 3      | 1       | 1    |
| Time | 2    | 3      | 1       | 1    |