**Industry 4.0 and Total Productive Maintenance Integrated System for Global Sustainability**

**Abstract**

**Purpose-** The integration of Total Productive Maintenance (TPM) and industry 4.0 (I4.0) is an emerging model, and the global pressure of various stakeholders raises scepticism of any emerging model towards providing sustainability. Therefore, this research aims to identify and rank the potential significant drivers of an integrated model of I4.0 and TPM to guide manufacturing enterprises towards sustainability.

**Methodology-** This research follows a four-phase methodology including literature review and expert opinion to select the sustainability indicators and I4.0 integrated TPM key drivers, followed by employing the Analytic hierarchy process (AHP) approach for weight determination of sustainability indicators. The research then deploys the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to prioritise the I4.0 integrated TPM key drivers based on their effect on various sustainability indicators. Finally, a sensitivity analysis is conducted to check the robustness of the TOPSIS.

**Findings-** The findings establish the top five most influential key drivers of an I4.0 integrated TPM system, which include Top management support, Formal I4.0 adoption program, Mid-management involvement and support, Solid TPM baseline knowledge, and High engagement of the production team. These top drives can lead manufacturing firms towards sustainability.

**Research implications/ limitations-** The digitalisation of shop floor practices, such as TPM could be adapted by shop floor managers and policymakers of manufacturing companies to deliver sustainability-oriented outcomes. In addition, this research may aid decision-makers in the manufacturing sector in identifying the most important drivers of Industry 4.0 and TPM, which will assist them in more effectively implementing an integrated system of Industry 4.0 and TPM to practice sustainability. The scope of TPM applicability is wide, and the current research is limited to manufacturing companies. Therefore, there is a huge scope for developing and testing the integrated system of Industry 4.0 and TPM in other industrial settings, such as the textile, food and aerospace industries.

**Novelty/originality-** This research makes a first-of-its-kind effort to examine how an I4.0 integrated TPM model affects manufacturing companies' sustainability and how such effects might be maximised.

**Keywords:** Industry 4.0, Total Productive Maintenance, Sustainability, Maintenance 4.0.

**1. Introduction**

Manufacturing sectors significantly impact business and engineering operations, strengthening their capacity for adaptation, sustainability, and efficiency while providing high-quality, low-cost products (Oztemel and Gursev, 2020). In addition to its growing importance to national GDP, manufacturing can also reduce poverty by providing opportunities for trained, semi-trained, and untrained workers (Amjad *et al.*, 2021). The contemporary civilisation has chosen sustainable development as a key strategic paradigm and a reaction to the rising ecological problem and massive socioeconomic inequities in worldwide progress (Christen and Schmidt, 2012).

In order to meet the standards of sustainability, current industrial processes provide various obstacles to manufacturing industries (Ahmad *et al.*, 2018; Thomas *et al.*, 2016). Manufacturing activities pose various sustainability-related responsibilities and threats due to their intensive resource use (Ahmad *et al.*, 2019). Sustainable manufacturing is the most feasible production technique in this situation (Ahmad and Wong, 2018). In both developed and emerging nations, the nexus between sustainability and industry is becoming a major discussion at a global level (Mathiyazhagan, 2021). To achieve more sustainable development programs, manufacturing companies need to develop more sustainable and resilient manufacturing processes (Haq and Boddu, 2017).

Lean manufacturing (LM) has been shown to be a critical strategy for companies aiming to ensure long-term sustainability (Barth and Melin, 2018; Filho and Barco, 2015). However, the success of LM depends on its various tools. According to Thanki *et al.* (2016), Total Productive Maintenance (TPM) is considered one of the most effective lean tools. TPM is a prevalent management concept that seeks to reduce breakdowns by employing a variety of complimentary maintenance concepts and strategies (Tortorella *et al.*, 2021). In order to increase shop floor productivity in developing countries at a time when capital cost levels are lower and new machinery acquisition demands more effort, the correct use of equipment and maintenance are essential (Jain *et al.*, 2014). TPM has proven to be an excellent functional method to improve manufacturing organisations' operational outcomes such as quality, price, delivery, and agility (Attri *et al.*, 2013).

TPM helps to reduce and optimise material consumption, pollutant emission, and energy consumption (Garza-Reyes *et al.*, 2018). Garza-Reyes *et al.* (2018)’s study further indicates that TPM positively influences the environmental performance of manufacturing firms. Additionally, the study of Chen *et al.* (2019) suggests that TPM positively affects environmental sustainability. Other past studies have also provided evidence that TPM contributes to achieving excellence in manufacturing operations. These studies have suggested that TPM leads manufacturing firms to achieve economic sustainability (Dieste *et al.*, 2021; Galeazzo, 2019; Galeazzo and Furlan, 2018). This functional outcome leads to a better reputation for manufacturing companies (Furlan *et al.*, 2011; Netland and Ferdows, 2014). Various TPM factors such as better health and a safe environment (Vukadinov *et al.*, 2018), effective communication between employees (Agustiady & Cudney, 2018), and top management (Singh and Gurtu, 2021) lead manufacturing companies towards social sustainability (Kiesnere and Baumgartner, 2020; Abid *et al.*, 2020; Staniškienė and Stankevičiūtė, 2018). Overall, this evidence suggests that TPM leads a manufacturing firm towards sustainability.

In 2011, the German government proposed Industry 4.0 (I4.0) as a phrase and strategic concept (Kagermann *et al.*, 2013). I4.0 is a natural outgrowth of decades of technological advancements in computer-integrated manufacturing and flexible manufacturing systems (Scheer, 2012). Kagermann et al. (2013) report suggest that cyber-physical systems (CPS) and intelligent technologies connecting machines, shop floor and business processes, consumers, end-users, and the entire supply chain are referred to as I4.0. Advanced technologies and CPS, with the help of artificial intelligence (AI) software, enable processes and equipment to communicate information, initiate operations, decide things, and control each other autonomously via the Internet of Things (IoT) (Kagermann *et al.*, 2013). This digitised industrialisation signified the beginning of an era for manufacturing organisations around the world, which may incorporate I4.0 technology into their business to improve operational outcomes such as costs, quality, productivity, scheduling, and product and service customisation (Chiarini *et al.*, 2020). Past studies suggested that I4.0 has the potential to deliver triple bottom line (TBL) sustainability (Birkel and Müller, 2021). According to Ghaithan *et al.* (2021), I4.0 improves the operational features and leads manufacturing firms towards economic sustainability. Similarly, the studies of de Sousa Jabbour *et al.* (2018) and Wang *et al.* (2016) indicate that I4.0 helps to deliver optimum use of resources and reduce the various wastes of production processes in manufacturing companies, leading to environmental sustainability (Ghaithan *et al.*, 2021). Also, implementing I4.0 in a manufacturing company improves various factors associated with social sustainability, e.g. safety of employees with a better workplace, and employee satisfaction (Kamble *et al.*, 2018).

With the advent of I4.0, manufacturing companies have been increasingly adopting cutting-edge digital technologies like big data, cloud computing, IoT, and machine learning (de Sousa Jabbour *et al.*, 2018). I4.0 is a technology-based production philosophy that integrates the cyber and physical worlds through enhanced automation (Xu *et al.*, 2018). The adoption of I4.0 technology significantly improves goods, operations, assistance, and overall business performance (Fettermann *et al.*, 2018). Past research has focused on integrating I4.0 into maintenance systems, but most of it has looked at predictive maintenance approaches in an I4.0 context (Dalzochio *et al.*, 2020; Zonta *et al.*, 2020). Tortorella *et al.* (2021) proposed and established an integrated Industry 4.0 and TPM system with the help of the diffusion of innovation theory (DIT). Their study offers the need to integrate I4.0 and TPM, and elaborates how I4.0 technologies are integrated into TPM philosophy. Further, they have empirically proved this integrated model with the support of industrial case studies of four companies.

Both TPM and I4.0 can contribute to achieving more sustainable operations in the manufacturing sector. Hence an integrated model of I4.0 and TPM may potentially lead a manufacturing firm towards sustainability. Nonetheless, it is crucial to understand the factors that may prompt their combination and how these may affect the attainment of more sustainable operations. After exploring the significant drivers and their influence on sustainability, comprehensive research of this integrated system could be demonstrated to achieve sustainability. In this line, no previous studies have investigated the effect of the I4.0 integrated TPM model drivers on the sustainability of manufacturing companies. To fill this gap in the academic literature, this study uses the hybrid AHP-TOPSIS methodology and consults industry and academia professionals with more than 20 years of experience and knowledge of I4.0 and TPM to define and rank the I4.0 integrated TPM model drivers. For that purpose, the following research questions are tackled in this study:

***RQ1-*** *What are the I4.0 integrated TPM model drivers in manufacturing companies to achieve sustainability?*

***RQ2-*** *How can the I4.0 integrated TPM model drivers in manufacturing companies be prioritised according to their influence on various sustainability indicators?*

The present research follows a four-phase procedure to address the above research questions. Initially, the drivers of the I4.0 integrated TPM model are identified from the literature and experts' help. Following, the weight of sustainability indicators is determined through the AHP method to understand their importance. In the following step, TOPSIS is applied to determine the rank of alternatives. The next step is a sensitivity analysis to ensure the reliability of the TOPSIS findings. Section 2 presents the literature on I4.0, TPM, and sustainability, followed by the research gaps identified in the relevant academic literature. Section 3 introduces the paper's methodology, followed by Section 4, which presents the results and discussion. Finally, Section 5 wraps the present study with conclusions, limitations and future research directions.

**2. Literature review**

**2.1 Industry 4.0, TPM, and Sustainability**

Manufacturers have faced serious challenges over the years as manufacturing industries have become more complicated, products have become more customised and service-oriented, and markets have become more efficient and flexible (Hopkins, 2021). The shift towards I4.0 has resulted in spectacular and rapidly shifting manufacturing, aided by Information and communication technologies (ICTs) that assist in curbing or overcoming those issues (Salkin *et al.*, 2018). The constant real-time interconnection of operations, machinery, goods, and services, as well as personnel, is the foundation of the I4.0. This validates I4.0's singularity in contrast to the three preceding industrial revolutions (Chiarini *et al.*, 2020). Parallelly, due to the sheer fast increasing population, resource scarcity, environmental degradation, land shortages, higher food requirements, and waste management, societies are worried about achieving sustainable development (SD) (Furstenau *et al.*, 2020).

Nevertheless, the investigation on SD reveals that organisations have often been judged primarily on their financial success and how well they function in terms of sustainability. Industry 4.0 provides a significant possibility for companies to accomplish sustainability (Stock and Seliger, 2016). Lower manufacturing and logistic costs, reduced lead times, and satisfied customers are all made possible through the digitisation aspects of Industry 4.0 technology, which in turn leads to more market share and greater profits (Stock and Seliger, 2016). Industry 4.0 technology helps to improve manufacturing flexibility and product quality, leading to the economic sustainability of manufacturing firms (Ghaithan *et al.*, 2021). Real-time data and data sharing among supply chain contributors help to allocate raw materials, water, energy, and labour time (de Sousa Jabbour *et al.*, 2018) and reduce resource evisceration, greenhouse gas emissions, and waste production (Wang *et al.*, 2016), leading to environmental sustainability (Ghaithan *et al.*, 2021). Incorporating Industry 4.0 technology in enterprises improves workplace conditions, ensures a safe working environment for employees, and introduces emerging technologies to employees, boosting motivation and morale, leading to social sustainability (Kamble *et al.*, 2018). It has been noticed that the deployment of technologies related to Industry 4.0 may aid in the achievement of the objective of conducting operations in an ethical and sustainable manner (Kumar *et al.*, 2020). Previous investigations between I4.0 and sustainability indicate that I4.0 positively influences the sustainability of manufacturing firms.

It is increasingly difficult for operation planners to maintain all the equipment due to the rising intricacy of industrial procedures and intelligent systems (Singh and Gupta, 2019). Malfunctions and faults of machinery most often lead to unfavourable impacts on the operation timeline, which in turn lowers customer service standards and increases operating expenses as a consequence of personnel having to spend extra hours and additional labour (Habidin *et al.*, 2018). When operations related to maintenance are not carried out in an acceptable manner, it has a negative impact on the revenue of the company (Poduval *et al.*, 2015). The primary goal of any maintenance programme is to keep units running as efficiently as necessary while minimising downtime and maintenance costs in order to prevent any severe breakdowns (Kumar *et al.*, 2021). The productivity of equipment, as well as their broad performance, may be significantly improved by using an effective maintenance management solution. It provides firms with a competitive advantage over their rivals (Singh *et al.*, 2016). TPM, one of the current maintenance methods, has gained popularity due to its favourable effects on the amount of time that machinery is idle and its overall efficiency (Nakajima, 1988). TPM is an important shop floor activity to achieve improved operational performance in manufacturing firms (Netland and Ferdows, 2014). TPM encourages operational consistency by ensuring that machinery is properly maintained, hence cutting down on breakdowns and improving safety as well as item grade (Wickramasinghe and Perera, 2016).

The relation of TPM with sustainability is observed as some researchers have established the relation between TPM and sustainability. For instance, Garza-Reyes *et al.* (2018) suggested that TPM tools reduce waste and simultaneously use optimal resources to deliver operational excellence. Moreover, Garza-Reyes *et al.* (2018)’s research was supported by Chen *et al.* (2019), whose research indicates that TPM has a major influence on the environmental performance of manufacturing companies, leading them towards environmental sustainability. Some recent studies support the fact that TPM offers economic sustainability in a firm by improving operational performance and optimising resources (Dieste *et al.*, 2021; Galeazzo, 2019; Galeazzo and Furlan, 2018). TPM is also associated with social sustainability factors of manufacturing firms that include employee health and a safer working environment, accident reduction at the workplace as well as the boosting of employee morale and satisfaction (Singh and Gurtu, 2021; Vukadinov *et al.*, 2018; Agustiady & Cudney, 2018).

The digitisation of maintenance enables a change away from policies of failure and responsive maintenance and toward policies of prediction and preventative maintenance, which provides a number of advantages on several fronts, including monetary, technological, and societal (Meqdadi *et al.,* 2020). The technologies of Industry 4.0 provide the groundwork for the digitalisation of maintenance and the enhancement of current procedures and approaches (Tortorella *et al.*, 2022). According to Silvestri *et al.* (2020), Industry 4.0 technologies such as big data may improve the ability to forecast normal lifetime phases while augmented reality may assist in the treatment and assessment of machinery malfunctions (Silvestri *et al.*, 2020). Other technologies that fall under the umbrella of Industry 4.0, such as the Internet of Things and cloud computing, make it possible to more effectively regulate and supervise working settings, therefore cutting down on waste and facilitating more decisive choices (Zheng *et al.*, 2021). One such significant impact of the digitisation of maintenance is the potential for the emergence of new regulations and responsibilities in order to accommodate developing technologies and novel maintenance procedures (Silvestri *et al.*, 2020).

The integration of I4.0 with TPM in large manufacturing enterprises was proposed by Tortorella et al. (2021) and demonstrated with the help of case studies. Their study also proposed some key drivers for the integrated I4.0 TPM model. Although previous studies have suggested that TPM and I4.0 help manufacturing companies achieve all three sustainability dimensions, no work has been conducted to investigate the I4.0 integrated TPM model from a sustainability context, even though sustainability is a pressing need for the current global manufacturing environment. Thus, this study contributes by addressing the following research gaps in the academic literature:

* Sustainability has not been investigated from an I4.0 integrated TPM context in manufacturing operations;
* The effect of I4.0 integrated TPM key drivers on sustainability has not been previously explored in past research; and
* The most important key drivers of an I4.0 integrated TPM system based on their effect on sustainability have not been studied in previous research.

**3. Methods**

This paper investigates the effect of various I4.0 integrated TPM model key drivers on the overall sustainability of manufacturing companies. The research followed four phases, namely: (1) selection of sustainability indicators and I4.0 integrated TPM key drivers, (2) Analytical hierarchy process (AHP), (3) Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and (4) Sensitivity analysis to complete the investigation of this study. The overall structure of the study is presented in Figure 1.

*“Insert Figure 1”*

**3.1 Phase 1: Selection of sustainability indicators and I4.0 integrated TPM key drivers**

This phase was based on a hybrid approach that included an extensive literature review and seeking input from experts to determine the sustainability indicators and I4.0 integrated TPM model key drivers. The research conducted by Swarnakar et al. (2021) was used as a source for the adaptation of 14 sustainability indicators that were used to portray the overall sustainability of manufacturing organisations. The 17 key drivers of the I4.0 integrated TPM model were also taken from the study of Tortorella et al. (2021). 21 experts were contacted through email and phone, from which 12 (57.14% response rate) agreed to participate (see Table I for details).

The 14 sustainability indicators and 17 key drivers for integrating I4.0 and TPM were then shared with the 12 experts to assess their reliability and validity in investigating the prioritisation of the key drivers of I4.0 integrated TPM model based on their effect on overall sustainability indicators. The timeframe of the experts’ responses was 15th February 2022 (responses sent) to 02nd March 2022 (responses received). After 15 days of rigorous discussion, the experts selected 13 drivers of I4.0 integrated TPM model and 10 sustainability indicators that they considered relevant to the study. This contributed to determining the sustainability indicators employed as the basis for this study and the I4.0 integrated TPM key drivers as an alternative. The process of selecting and deducting the drivers and indicators is adapted from Orji and Liu (2021), and given in Appendix 1.

*“Insert Table I”*

**3.2 Phase 2:** **Analytic hierarchy process (AHP)**

After determining the sustainability indicators that represented the overall sustainability of a manufacturing firm, these were ranked based on their importance. Multiple methods that include the alpha-Discounting approach introduced by Smarandache (2010) are available in the literature. However, AHP is often used in similar situations where subjectivity arises in the decision-making process and where this process is established based on some criteria in the hierarchy (Tzeng and Huang, 2011). AHP is a powerful problem-solving method for unclear matters with difficult quantitative assessments (James *et al.*, 2021). Table II presents the value allocation for AHP in a pairwise comparison matrix.

*“Insert Table II”*

To establish priority scales, AHP uses pairwise comparisons and is based on the subjective judgements of domain experts (Saaty, 2008). The Steps of the AHP method were adapted from Saaty (2008), and these are presented in Appendix 2.

For the AHP method, the value of the random index (RI) was also adapted from Saaty (2008), see Table III.

*“Insert Table III”*

**3.3 Phase 3:** **Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)**

In a “multi-criteria decision method” (MCDM), the alternative ranking comes after criteria weighting. Aruldoss *et al.* (2013) suggest that TOPSIS plays a significant role in all other MCDM techniques. Thus, the ranking of alternatives is determined with the help of TOPSIS approach in this phase. TOPSIS is a MCDM method that considers how far away each alternative is from one another and how far away it is from the ideal negative point (Benítez *et al.,* 2007). In other words, the optimum option should be the one that is closest to the positive ideal solution (PIS) and the furthest away from the negative ideal (Chen *et al.*, 2006). The TOPSIS method uses the attribute/criterion weights assigned to each alternative to generate a decision matrix and a normalised decision matrix (Karim and Karmaker, 2016). Table IV presents the linguistic values used in TOPSIS with their equivalent numerical values.

*“Insert Table IV”*

The steps of TOPSIS method followed in the presented research were adapted from James *et al.* (2021) and Hwang and Yoon (1981).

**Step 1: Normalise the decision-matrix**

Once beneficial and non-beneficial criteria have been chosen, the normalised decision matrix may be generated using the following formula-

(1)

Where, is the original and is the normalised score of the decision matrix.

**Step 2: Calculate the weighted normalised decision matrix**

Weighted normalised decision matrices are generated by multiplying the normalised matrix by the criterion's weight.

(2)

**Step 3: Determine the positive ideal and negative ideal solutions**

TOPSIS attempts to quantify how far each alternative is from both positive and negative ideals. We use the following formulae to find the positive and negative ideal solutions.

So that

(3)

(4)

Where j1 represents the negative criterion and j2 represents the positive criterion.

**Step4: Extent to which positive and negative ideal solutions are deviated from**

The TOPSIS approach assigns a score to each alternative depending on how close it is to the positive ideal and how far it is from the negative ideal. Therefore, the following formulae are used to determine the distances between each reasonable alternative and the ideal positive and negative solutions at this point.

(5)

(6)

**Step 5: Calculate the relative closeness degree of alternatives to the ideal solution**

In this step, the following equation was used to determine how close each potential answer is to the optimal one. Intuitively, the closer the relative closeness degree is to 1, the more closely the alternative resembles the positive ideal solution and the more it differs from the negative ideal solution.

(7)

After determining the closeness coefficient, the alternatives are sorted, with the closest option placed first.

**3.3.1 Reason for selecting the AHP-TOPSIS combined approach**

AHP varies from TOPSIS in two ways. Firstly, there is a pairwise comparison of criteria and alternatives in AHP, whereas in TOPSIS there is not (Baykasoglu *et al.*, 2013). Secondly, AHP uses criteria and alternative hierarchies while TOPSIS does not. Moreover, the AHP procedure guarantees consistency in the development and judgment of CI, but TOPSIS cannot guarantee controlled consistency due to the lack of comparative indicators (Hadikurniawati *et al.*, 2018). One key constraint of AHP is its ability to implement cases with numerous criteria and alternatives. TOPSIS, on the other hand, can be incorporated in these cases because its method is straightforward and liberated of any computation problems, including for huge datasets (Hadikurniawati *et al.*, 2018). TOPSIS methods, however, require support from other research methods that would offer the comparative significance of different criteria/attributes relevant to the objectives, and AHP is particularly fit in this context (Rao and Davim, 2008). Some recent studies have adapted the hybrid approach of AHP and TOPSIS (Mojaver *et al.*, 2022; James *et al.*, 2021; Axelsson *et al.*, 2021). This evidence and arguments motivated this research to adopt a combined approach of AHP and TOPSIS.

**3.4 Phase 4:** **Sensitivity Analysis**

The reliability of the procedure used in this research was evaluated by employing a sensitivity analysis. With the aid of the AHP and TOPSIS techniques, the relative importance of the 10 sustainability indicators and the 13 alternatives was assessed. In this study, 11 scenarios were conducted to perform the analysis by varying the weight of the different criteria. The methodology for the sensitivity analysis was adapted from the work of Singh and Sarkar (2019). Ten sustainability indicators were used as a criterion in the present research. Therefore, ten different scenarios were possible for different weights of each criterion. Also, one scenario with equal weight for each criterion was possible. In this way, 11 scenarios were used to carry out the sensitivity analysis. For ten scenarios, one criterion was given a maximum weight (0.4) while the remaining nine criteria were given a similar weight (0.6/9 = 0.067). For the last scenario, each criterion was given a similar weight (1/10 = 0.1). For these scenarios, the ranking of alternatives was determined, and the variations in the results were investigated through a sensitivity analysis.

**4. Results**

**4.1 Phase 1: Literature review and experts’ opinion to select the alternatives and criteria**

During this stage, a team of industry professionals, including shop floor managers, TPM consultants, sustainability experts, and practitioners of Industry 4.0, were brought together to establish an expert group. These professionals had the duty of determining and assessing the factors that drive the integrated TPM model of Industry 4.0, as well as the indicators of sustainability that were extracted from the literature review. The opinions of these industry leaders and a comprehensive review of the relevant research were used to determine the primary drivers (alternatives) and indications (criteria). A panel of industry experts was assembled in order to rank the importance of the primary drivers of the Industry 4.0 integrated TPM model according to the impact that they had on a variety of sustainability metrics. Following an exhaustive literature analysis and consultation with subject-matter experts, 10 sustainability indicators were specified as criteria, and thirteen drivers from the I4.0 integrated TPM model were chosen as alternatives. The selected indicators and drivers for this study are presented in Tables V and VI respectively.

*“Insert Table V”*

*“Insert Table VI”*

**4.2 Phase 2: Determination of the relative importance of each of the indicators of sustainability using AHP**

After the selection of criteria and alternatives, the AHP method was applied to conduct a weight assessment of the criteria selected for this study. The list of the selected criteria was provided to the experts for pairwise comparison as per their judgement interpretation, see Table II. After the decisions of experts, the decision matrix ‘M’ (12) was constructed and expressed further.

(12)

By carrying out the steps outlined in Appendix 2 for the AHP analysis, the normalised weight and ranking of sustainability indicators were computed and established. Table VII presents the normalised weight and ranking of sustainability indicators.

*“Insert Table VII”*

As shown in Table VII, according to the Sustainability Indicators, C4 is the first priority. The next priorities are assigned to C7, C2, C9, C10, C5, C1, C3, C6 and C8 according to the obtained weights.

**4.3 Phase 3: Assessment and prioritisation of the Industry 4.0 integrated TPM model key drivers for achieving sustainability using TOPSIS**

After the selection of the relative weight of the selected criteria was computed, the TOPSIS method was used to select the best drivers of the I4.0 integrated TPM model that met the sustainability (selection) criteria. As shown in Table VII, all criteria were beneficial. The experts provided their input in terms of numeric value, see Table IV, to select the best alternative for the selected criteria. The combined decision matrix after the experts’ opinions is presented in Table VIII.

*“Insert Table VIII”*

After constructing the combined decision matrix, the normalised decision matrix, see Table IX, was computed with the help of equation 1.

*“Insert Table IX”*

After that, the weighted normalised decision matrix was computed with the help of equation 2. This is presented in Table X.

*“Insert Table X”*

In order to determine how far each alternative was from the positive and negative ideals, we solved these solutions using equations 3 and 4. Table XI displays the optimal values (both positive and negative).

*“Insert Table XI”*

After computing the positive and negative ideal solutions, the distance of each alternative from the positive and negative ideal was calculated according to the assigned values. With the help of equations 5 and 6, the assigned values were computed to deliver the positive and negative ideal points. Table XII presents the calculated values of alternative distance to positive and negative ideal points.

*“Insert Table XII”*

Finally, the relative closeness degree of each alternative to the ideal solution was computed with the help of equation 7, while the ranking of alternatives was determined accordingly. The results are presented in Table XIII.

*“Insert Table XIII”*

The ranking of I4.0 integrated TPM model key drivers was ascertained based on the value of the relative closeness degree of each alternative to the ideal solution shown in Table XIII, with A6 ranking first with the highest relative closeness degree value of 0.844. The following were the results of the ranking of I4.0 integrated TPM model key drivers to deliver sustainability: A6>A3>A8>A13>A11>A12>A4>A7>A5>A10>A2>A9>A1. According to the findings, Business ‘Experience with I4.0’ (A1) had the least relative closeness degree value, implying that it has the least influence on sustainability compared to other I4.0 integrated TPM model key drivers.

**4.4 Phase 4: Robustness assessment of the method using sensitivity analysis**

After the ranking determination from TOPSIS, the sensitivity analysis was conducted, as indicated in Section 2.4, to check the robustness of the alternative rankings. Sensitivity analysis explains the consistency of the method (Lima-Junior and Carpinetti, 2016).

*“Insert Table XIV”*

*“Insert Figure 2”*

The ranking variation of alternatives due to variation in the weight of the criteria is shown in Table XIV and Figure 2. These show that A6 has the highest weight in ten scenarios (except S7). A3 has the highest weight in one scenario (S7), and the second-highest weight in six scenarios (S3-S5, S8, and S10, S11). The results of the sensitivity analysis indicate that the weight of the criteria has a significant impact on the ranking of other alternatives. However, the order of the top five ranking alternatives is the same in most cases. This indicates that the method and its findings are consistent and robust.

**5. Discussion**

In the modern world, the operations of manufacturing companies come with a variety of obligations and dangers connected to sustainability as a result of their intense use of resources. Therefore, there is significant pressure on manufacturing companies to achieve sustainability requirements since sustainable manufacturing is widely recognised as a production method that is the most viable given the current circumstances. The fourth industrial revolution has seen the development of new technologies and the operation of machines. The dependability of manufacturing companies is mostly dependent on the effectiveness of their machinery and maintenance. As a result, the drivers of integrated TPM and Industry 4.0 models may be an effective option for manufacturing organisations that are looking to achieve results that are focused on sustainability. Thus, it is necessary to determine the drivers of the integrated TPM model for Industry 4.0 in order to offer sustainability in manufacturing companies. Because it is difficult to develop and deploy all of the drivers at the same time, these need to be prioritised so that decision-making may be made more effective. To rank the drivers that contribute to sustainability in manufacturing firms, this research employs a technique that is a combination of the AHP and TOPSIS methods. Therefore, the present research identifies and prioritises the key drivers of an Industry 4.0 integrated TPM model to achieve the sustainability of the manufacturing firm.

The findings of the research indicate that ‘Top management support’ (A6) is the most important and influential I4.0 integrated TPM model key driver for achieving sustainability in a manufacturing organisation. It indicates that top management support should be taken as a priority while implementing a manufacturing system that integrates I4.0 and TPM. This outcome supports the results of recent studies, i.e. Jayashree *et al.* (2021), Kiesnere and Baumgartner (2020), and Kiesnere and Baumgartner (2019), which suggest that top management plays an important role in achieving sustainability in manufacturing firms and that it leads manufacturing companies towards sustainable development. Top management ensures that adequate resources are allocated to incorporate new and emerging technologies, into the operations of a company, to support sustainability (Reyes *et al.*, 2016), which could be a possible explanation for the current findings.

The second most influential I4.0 integrated TPM model key driver was determined to be the ‘Formal I4.0 adoption program’, which also leads a manufacturing firm towards sustainability. According to the results of this research, the formal adoption of a program to officially implement I4.0 technologies in a manufacturing company is an essential factor for these technologies to effectively work alongside traditional LM approaches such as TPM and support the company’s transition towards more suitable operations. Past research has suggested that the implementation of I4.0 in a manufacturing firm helps to achieve the sustainability dimensions (Ghaithan *et al.*, 2021; de Sousa Jabbour *et al.* 2018; Kamble *et al.*, 2018; Wang et al., 2016). Thus, this outcome supports these studies.

The third most important driver of the I4.0 integrated TPM model resulted to be ‘Mid-management involvement & support’. The function of middle management extends far beyond the administration and execution of top management's strategic decisions. Middle managers interconnect and integrate potentially divergent perspectives from inside and outside the firm, and they connect top managers' strategic intents with lower management and operational plans and operations (Posch and Speckbacher, 2017). This could be a possible reason for this result. Furthermore, this study argued that middle management must be actively involved in discussing potential actions and considering their larger economic, social, and environmental consequences in order to effectively implement sustainability initiatives. Thus, this result supports the previous work of Posch and Speckbacher (2017) and Godkin (2015), which suggest that middle management involvement and its support play an essential role in achieving sustainability.

The fourth most influential I4.0 integrated key driver is a ‘Solid TPM baseline knowledge’ to achieve sustainability in a manufacturing organisation. Solid TPM baseline knowledge helps a manufacturing firm to implement and practice TPM formally and practically. TPM implementation in manufacturing firms leads to optimal material use, reduced accidents, safer and healthier work environments, and other sustainability factors. This could act as the possible reason for this result. Thus, this outcome supports the many previous studies from Dieste *et al.* (2021), Galeazzo (2019), Chen *et al.* (2019), Galeazzo and Furlan (2018), Garza-Reyes *et al.* (2018) and Agustiady and Cudney (2018), which indicate that TPM implementation leads an organisation towards various sustainability dimensions.

The fifth important driver I4.0 integrated TPM model system to achieve sustainability is ‘High engagement of production team’. This result supports the work of Carmeli *et al.* (2017) and Longoni *et al.* (2014). The participation of employees produces a more participatory work environment, in which employees are invigorated and more devoted to the organisation, which ultimately results in higher satisfaction (Longoni *et al.*, 2014). This could explain the reason for this result.

The findings of this study helped to identify the top five I4.0 integrated TPM model key drivers that can assist manufacturing firms in practising sustainability. The next parts explore the study's theoretical and managerial implications.

**5.1 Managerial and theoretical implications**

This study adds to the existing TPM, Industry 4.0, and sustainability literature as well as sheds light on how manufacturing companies might advance toward more sustainable operations while using I4.0 integrated TPM model production systems. In terms of the theoretical implications drawn from the research and its findings, it represents the first endeavour to fill a gap in the academic literature by examining and stressing the importance and effects of an integrated I4.0 and TPM model as key drivers in manufacturing companies as well as understanding their impact on sustainability indicators. In this regard, the study can be used as a model for studying the I4.0 integrated TPM model's main drivers in manufacturing companies of developing nations.

The link between sustainability and industry is becoming a major topic of discussion at a worldwide level in both developed and developing countries (Mathiyazhagan, 2021). Some past research has studied the effect of TPM and I4.0 on the sustainability of manufacturing firms. However, these researches are based on the separate effect of TPM and I4.0 on sustainability. Thus, the understanding of the potential impact of an I4.0 integrated TPM model on sustainability is still limited. This study addresses a research gap.

In terms of the managerial implications of the current research, manufacturing firms were used as the study's foundation. The primary focus of manufacturing companies has been on economic sustainability, whilst the global manufacturing environment has tended to focus on overall sustainability. As a result, sustainability and how new emerging technologies such as I4.0 integrated TPM model might migrate to these practices have received very little attention. The findings of this study can help manufacturing firms determine which influential I4.0 integrated TPM model key driver can help them achieve sustainability more effectively. As a result, managers in manufacturing organisations can concentrate on the most influential I4.0 integrated TPM model key driver rather than the total I4.0 integrated TPM model key driver when it comes to attaining sustainability in their businesses. For example, depending on the top 5 I4.0 integrated TPM model key drivers, they can develop tailored training programmes in their organisations. It will empower their employees and systems in achieving sustainability more efficiently. Similarly, decision-makers and policymakers in manufacturing companies may use this research to assess sustainability in their firms and design appropriate I4.0 integrated TPM model implementation policies to improve sustainability.

Our study makes a practical contribution by suggesting potential avenues for the digitisation of maintenance. In addition, the findings of our study provide advice for managers to better understand the combination of TPM practices and I4.0 technologies that are more appropriate when considering the sustainability of manufacturing enterprises (i.e. social, economic, and environmental). With this information, managers can prioritise the drivers according to the requirements of sustainability in their manufacturing companies. The prioritisation of drivers of an Industry 4.0 integrated TPM model helps to focus on various drivers as per their ranking to deliver more effective sustainability outcomes within the manufacturing sector. For instance, while implementing the Industry 4.0 integrated TPM model, top management can help in two aspects: first, it can help to implement this integrated model more effectively (as they are the major player when implementing new managerial practices within firms), and second, top management can help to develop an integrated model in a way that firms can achieve social, economic, and environmental sustainability. The implication could be understood as the integrated Industry 4.0 and TPM model can offer safer working environments by reducing accidents (with real-time monitoring of equipment), better economical outcomes (with better operational outcomes), and better ecological results (with optimal use of resources and reduction of wastes).

**6. Conclusions, limitations and future scope**

This study deals with the practical and theoretical challenges associated with the impact of an I4.0 integrated TPM model system on the sustainability of manufacturing organisations. Also, it is one of the first research to look into the impact of an I4.0 integrated TPM model system on the sustainability of manufacturing companies. This research addresses some knowledge gaps and contributes to our understanding of I4.0 when integrated with TPM as well as sustainability by:

• Investigating the influence of an I4.0 integrated TPM model system on the sustainability of manufacturing enterprises.

• Exploring the needed sustainability indicators in the context of an I4.0 integrated TPM system through an extensive literature review and experts’ opinions.

• Establishing the ranking of the I4.0 integrated TPM model’s key drivers based on their influence on different sustainability indicators to investigate its most influential key drivers to achieve sustainability in manufacturing organisations.

Such results are helpful to factory managers seeking to introduce novel hybrid ideas, like an I4.0 integrated TPM model, into their organisations to achieve long-term sustainability. Due to the widespread adoption of both methodologies, the I4.0 integrated TPM model system may prove useful in promoting sustainability in industries as diverse as textiles, aerospace, food production, and automobiles. These industries are under ongoing international pressure to implement sustainable practices in their operations, and an I4.0 integrated TPM model approach might be a significant contributor to achieving this goal.

Ultimately, the research offers valuable insights into the managerial implications of I4.0 integrated TPM model implementation on the sustainability of manufacturing firms, promoting its consideration in this manner. As a result, it presents proof for management professionals of aspects that might perform a substantial factor in accomplishing sustainability through I4.0 integrated TPM model implementation, particularly through considering the most impactful key drivers. Hence, statistically verifying the suggested idea by ranking I4.0 integrated TPM model key drivers based on their impact on numerous sustainability indicators of manufacturing firms, as well as their propositions, might be regarded as the next step in closing the gap between concepts and reality.

Despite its sound methodology, this work contains a number of shortcomings. To begin with, the research was restricted to only manufacturing firms. As a result, additional research is necessary to offer more perspectives on managerial aspects of an I4.0 integrated TPM model's effect on sustainability in other sectors, including services, logistics and healthcare. This type of research will shed more light on the function of industry features in I4.0 integrated TPM model effect on sustainability. The current research is based on Indian manufacturing organisations. Hence, global research in the same context could be proposed to deliver a more comprehensive study. Small and medium enterprises (SMEs) have been significant facilitators of the economic development of nations. Therefore, in future, the assessment of sustainable outcomes when implementing an Industry 4.0 and TPM integrated system could be developed and tested theoretically and practically. Lastly, a multiple case study approach can add some real insights by validating the effect of an I4.0 integrated TPM model on sustainability in a real industrial scenario.

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