

Analysing Critical Factors of Strategic Alignment Between Operational Excellence and Industry 4.0 Technologies in Smart Manufacturing

Abstract

Purpose- The manufacturing sector is highly competitive and operationally complex. Therefore, the strategic alignment between operational excellence methodologies and Industry 4.0 technologies is one of the issues that need to be addressed. The main aim of the study is to determine the critical factors of strategic alignment between operational excellence methodologies and Industry 4.0 technologies for manufacturing industries and make comparative analyses between automotive, food, and textile industries in terms of strategic alignment between operational excellence methodologies and Industry 4.0 technologies.

Design/methodology/approach- Firstly, determining the critical factors based on literature review and expert opinions, these criteria are weighted, and Analytical Hierarchy Process is run to calculate the weights of these criteria. Afterwards, the best sector is determined by the Gray Relational Analysis method according to the criteria for the three manufacturing industries selected for the study.

Findings- As a result of AHP, *'Infrastructure for Right Methodology, Techniques and Tools'* is in the first place, *'Organizational Strategy'* is in the second place, while the third highest critical factor is *'Capital Investment'*. Moreover, based on Gray Relational Analysis results, the automotive industry is determined as the best alternative in terms of strategic alignment between OPEX methodologies and I4.0 technologies.

Originality- This study is unique in that it is primarily possible to obtain the order of importance within the criteria and to make comparisons between three important manufacturing industries that are important for the economies of the world.

Keywords: Operational Excellence; Critical Factors; Industry 4.0 technologies; Smart Manufacturing; Organizational Strategy

1. Introduction

With the effect of increasing competition in the globalizing world, companies need to perform at the highest level to maintain their presence in the market and increase their competitiveness (Castelo-Branco et al., 2019; Muhammad et al., 2022). Recently, companies that know it is not enough to perform well to exist in the market have realized the necessity of making more sustainable progress (Bagnoli et al., 2022). Companies have to adopt competitive strategies to

protect their current needs to be exemplary not only in their sectors but also in all related sectors (Kharub et al., 2022). One of these strategies is operational excellence (OPEX); for companies to survive, excellence is no longer an option. It has become a prerequisite for success (Ramadan et al., 2022).

OPEX is a continuous improvement philosophy that aims to increase the value created by the businesses for their customers and to use the business resources effectively while increasing this value (Madhavika, 2021) and Lean Management, 6 Sigma (Kaswan et al., 2022) are some of OPEX methodologies that are accepted worldwide (Muhammad et al., 2022). In today's conditions, where competition is increasing and survival is possible with innovative solutions, OPEX is one of the essential factors that will contribute to the sustainable performance and growth of the organization (Luz Tortorella et al., 2022). Companies that use the OPEX strategy gain numerous advantages and have a chance of sustainable development despite challenging competitive conditions (Muazu et al., 2021).

Industry 4.0. (I4.0) is beneficial in manufacturing processes as it provides more accurate and faster data, provides more support in understanding customer demands, and helps measure solutions' persistence and effectiveness (Psarommatis et al., 2022). I4.0 accelerates the adoption of OPEX methodologies, especially approaches such as lean management and 6 Sigma (Antony et al., 2022; Carvalho et al., 2022). In other words, I4.0 provides more resources and opportunities for the manufacturing sectors to adopt OPEX methodologies (Luz Tortorella et al., 2022). Especially in the automotive, food and textile industries, integrating OPEX methodologies and I4.0 technologies is one of the most critical sectors in terms of the complexity of operations, a large number of stakeholder structures, and the need for technology and lean applications in their business models (Wankhede & Vinodh, 2022). These industries maximize operational efficiency, generate more added value by raising asset and equipment performance, manage all facilities together and from a single center, secure and versatile data sharing and continuity with operation teams and field operators (Sassanelli et al., 2022). Ensuring that unexpected downtimes are kept to a minimum is a highly critical issue (Nhelekwa et al., 2022). Therefore, these sectors need to be analyzed in terms of strategic alignment between OPEX methodologies and I4.0 technologies.

Therefore, as a motivation for the study, implementing methodologies that can be used to achieve OPEX in an integrated manner with I4.0 technologies is one of the issues that need to be addressed. It has become imperative to ensure OPEX, especially in manufacturing industries

where operational problems are encountered and where the competitive environment is very high. Hence, the research questions are summarized below;

- **RQ1:** What are the critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries?
- **RQ2:** Which manufacturing industries perform better according to critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for selected manufacturing industries?

To answer the research questions, firstly, after determining the critical factors based on literature review and expert opinions, they are weighted with the Analytical Hierarchy Process (AHP) method. Afterwards, the best sector is determined by the Gray Relational Analysis (GRA) method according to the criteria specified among the 3 manufacturing industries selected for the study. To sum up, the study's main aim is to determine the critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries and make comparative analyses between automotive, food and textile industries in terms of strategic alignment between OPEX methodologies and I4.0 technologies.

The study's structure follows; Section 2 covers a literature review based on critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries. Section 3 consists of methodology, which is AHP and GRA. Section 4 highlights the implementation and results of these methods. Section 5 includes discussions and implications and lastly the conclusions.

2. Literature Review

OPEX is to manage the increasingly competitive environment and complexity today by using the right methods (Tripathi et al., 2022). OPEX is one of the business strategies, which is more consistently and reliably than the competition, with lower operational risk, operating costs and increased revenues compared to its competitors (Jengwa & Pellisier, 2022). For some companies, OPEX means the correct and consistent implementation of some basic methodologies (Six Sigma, Lean, TQM, TPM, etc.) (Buer et al., 2018) and tools (Kaizen, SMED, DMAIC, Kanban, Visual Management, etc.) (Ramadan et al., 2022). For leaders, OPEX is defined as correct process practices and good management of business processes (Dev et al., 2020). OPEX can also be defined as creating the right business culture (Wahab et al., 2022).

OPEX methodologies are very comprehensive and are applied according to the needs of the process (Found et al., 2018). The OPEX methodologies mentioned in this study are 5S, 6 sigma, lean management, Kaizen, SMED, Kanban, risk management, SWOT analysis etc. (Ramadan et al., 2022). However, knowing only OPEX methodologies in the manufacturing industry is not enough (Luz Tortorella et al., 2022). Within the scope of I4.0 technologies, artificial intelligence, robotic process automation, machine learning, internet of things, cloud computing, big data, data analytics, advanced robotics, 3D Printing and mobile applications are some of the I4.0 technologies that lead the manufacturing industry in particular (Javaid et al., 2022).

As mentioned before, it is essential to integrate these technologies into operations and to make this integration permanent. Making I4.0 technologies permanent in operations is possible with OPEX methodologies (Sassanelli et al., 2022). OPEX is a process that strives for better key performance metrics (Muhammad et al., 2022) and algorithms, machine learning, and other artificial intelligence applications can be used to collect these metrics (Luz Tortorella et al., 2022). Moreover, using sensors and software technologies in operational processes for OPEX provides process control (Gupta et al., 2020).

Considering the literature review, OPEX methodologies, and I4.0 are topics that have been studied separately in the literature for a long time. The importance (Wahab et al., 2022), concept (Muhammad et al., 2022), and definition and usage of OPEX methodologies (Nayak and Choudhary, 2022) are some of the most studied subjects in the literature. Similarly, the definition, concept (Krstić et al., 2022) and application areas of I4.0 (Hassoun et al., 2022) take up much space in the literature. For example, Luz Tortorella et al. (2022) focused on the meaning of OPEX in the I4.0 era. They implemented a survey to define OPEX and its key aspects in the I4.0 era. One of the aims of this study indicates definitions and benefits of OPEX in the I4.0 period.

Moreover, Miandar et al. (2020) studied the integration between OPEX and I4.0 via by systematic literature review. They provide increased understanding and knowledge about integration between OPEX and I4.0. Similarly, Trakulsunti et al. (2022) focused on a systematic literature review of OPEX methodologies. In addition, Tissir et al. (2022) studied the integration between lean six sigma, one of the OPEX methodologies and I4.0. They aimed to find research gaps in this issue and highlight new study ideas. However, when considering literature in general, it is seen that the studies on the strategic alignment of OPEX methodologies with I4.0 are quite a few.

As it can be understood from the studies described, there are hardly any studies, especially in the manufacturing industry. For this reason, this study has been prepared to fill the gap in the literature on the strategic alignment of OPEX methodologies with I4.0 in the manufacturing industry. Because it is undisputed that the integration between OPEX methodologies with I4.0 provides several benefits to the manufacturing industries (Luz Tortorella et al., 2022). Therefore, in the following section, critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries are explained in detail.

2.1. Critical Factors of Strategic Alignment between OPEX Methodologies and I4.0 Technologies for Manufacturing Industries

The manufacturing sector is highly competitive and operationally complex (Luz Tortorella et al., 2022). With today's rapidly changing world order and globalization, the emergence of new technologies daily shows that the production sector should always be dynamic (Psarommatis et al., 2022). Therefore, the integration of OPEX methodologies in manufacturing industries with I4.0 technologies and other digital applications provides benefits such as increasing total equipment efficiency, maximizing value-added activities (Tissir et al., 2022), eliminating waste, increasing efficiency, reducing costs, producing quality products according to customer demand, and increasing customer satisfaction accordingly (Trakulsunti et al., 2022).

This means that important factors need to be addressed to establish strategic alignment between OPEX methodologies and I4.0 technologies in manufacturing sectors (Bhat et al., 2022). These factors enable the establishment of strategic alignment between OPEX methodologies and I4.0. For this reason, in the next section, critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries are explained as shown in Table 1.

Table 1. Critical Factors of Strategic Alignment between OPEX methodologies and I4.0 Technologies for Manufacturing Industries

Symbolize	Critical Factors	Explanation	References
CF₁	Resource Allocation	While I4.0 provides resource allocation, improvement is achieved in resource allocation together with OPEX strategies. For this reason, strategic alignment between OPEX strategies and I4.0 is essential for resource allocation in manufacturing.	Jaskó et al. (2020); Grillo et al. (2022)
CF₂	Capital Investment	While I4.0 adaptation requires high-cost investments, more investment is needed for its integration with OPEX strategies. The accuracy and amount of investments are critical to ensure strategic alignment between OPEX strategies and I4.0 technologies for manufacturing industries.	Charro & Schaefer (2018); Caiado et al., (2022)
CF₃	Organizational Strategy	For strategic alignment between OPEX strategies and I4.0 applications, the methods followed and the strategies adopted by the institutions should always be innovative.	Virmani & Salve (2021); Muhammad et al. (2022)
CF₄	Employee Involvement	Employee involvement is one of the most critical elements to ensure a new technological adaptation in manufacturing processes. To ensure strategic alignment between OPEX strategies and I4.0 applications, employee involvement should be provided and policies should be adopted for this.	Bhat et al. (2022); Tripathi et al. (2022)
CF₅	Infrastructure for Right Methodology, Techniques and Tools	It is necessary to apply techniques, tools and methods for OPEX strategies. In I4.0 integration, it is essential to plan the infrastructure in a way that will provide the OPEX methodology for strategic alignment between OPEX strategies and I4.0 technologies for manufacturing industries.	Grandinetti et al. (2020); Caiado et al., (2022)
CF₆	Top Management Support	Providing a new adaptation in the manufacturing industry requires the support of the top management.	Surianarayanan & Menkhoff (2020); Trakulsunti et al., (2022)
CF₇	Information Sharing	Ensuring strategic alignment between OPEX and I4.0 is extremely important in providing complete and accurate information sharing between the processing times and tracking records of automation data and between the entire manufacturing processes.	Dev et al. (2020); Keivanpour (2022)

To answer the first research question, the AHP method is used for weighting these criteria and for the second research question GRA method is used. Therefore, in the following section, these methods are discussed.

3. Methodology

This study aims to answer the first research question, which is what are critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries. Then, according to the weights found, it is aimed to specify the best sector among 3 important manufacturing sectors that play an important role in the manufacturing industry according to critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries. Therefore, the flow of the methodology is given in Figure 1.

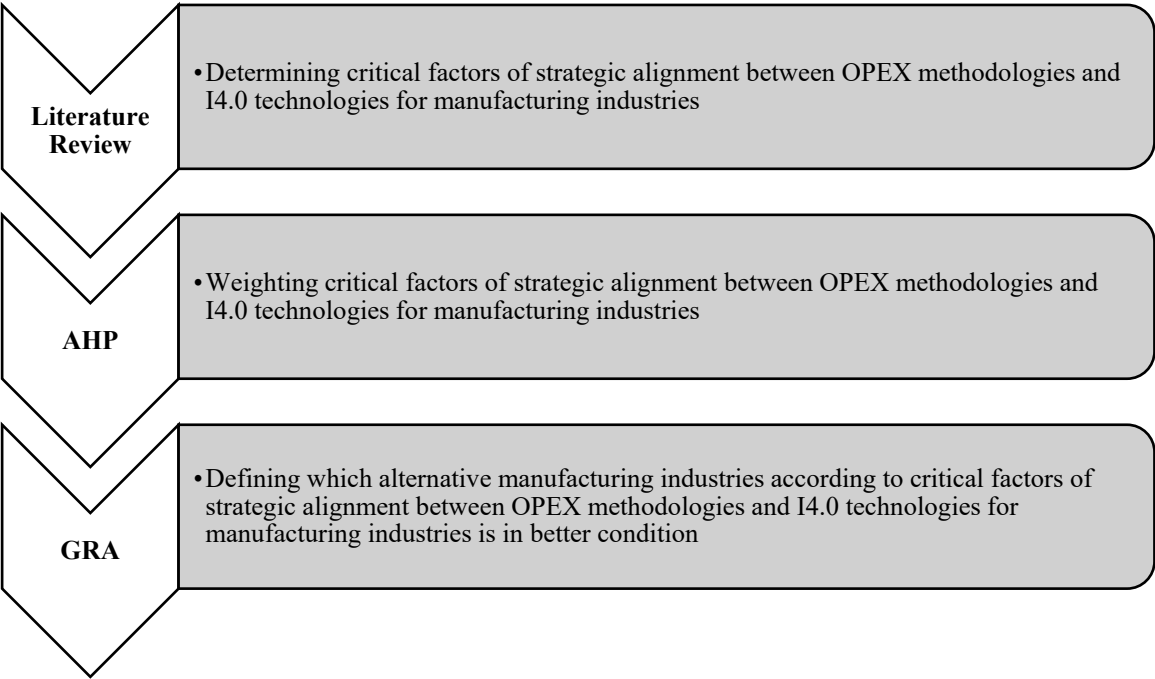


Figure 1. Flow of the Methodology

As seen in Figure 1, critical factors were determined as a result of the literature review. After that, AHP is used for critical weighting factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries. Then, the GRA method is used to define alternative manufacturing industries, according to critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries is

in better condition. AHP is the most preferred method for criterion weighting (Topno et al., 2022). It proves its reliability with the consistency rate obtained at the end of the method (Karaaslan et al., 2022). Although different weighting methods such as SWARA, SMART i.e. can be used instead of the AHP method, the AHP method was preferred in this study to easy collect the information sharing of the experts (Veisi et al., 2022) and the consistency of the results (YU & Hong, 2022). Moreover, AHP is a method in which the knowledge, experience, thoughts and intuitions of the individual are logically combined (Kumar & Singh, 2022).

GRA has become a method that is used more and more in the literature as a decision-making method (Zhang et al., 2022). Applications in which GRA is used in different areas reveal the applicability of the method more (Mahmat et al., 2022). GRA method can be used to measure the relationship between two sequences numerically and logically (Wen et al., 2022). It can numerically calculate the relationship between the sequences to be compared for this process, and the degree of relationship calculated as a result of the operations is called the gray relationship degree (Zhang et al., 2022). For these reasons, the application of this article gained priority in the literature, and the application of AHP and GRA methods was preferred in terms of reliability and ease of getting opinions from experts.

Before moving to the implementation of the AHP and GRA methods, these are briefly discussed.

3.1 AHP

AHP, a quantitative and qualitative method developed by Saaty, helps decision-makers in multi-criteria under uncertainty by including their experience and knowledge in the decision (Saaty, 2008). AHP helps to solve complex problems where the decision maker develops an understanding of the definition and elements of the problem (Benítez et al., 2012). AHP allows the inclusion of subjective and objective thoughts on the problem in the decision process (Saaty & Vargas, 2012). AHP has 4 main steps;

Step 1: Creating Hierarchical Structure and Formulating the Problem

Step 2: Build the Pairwise Comparison Matrix and Determine the Weights

Depending on the expert opinions, a pairwise comparison matrix in $n \times n$ size is obtained.

Step 3: Determining the Relative Weights of the Criteria

$$w_i = \frac{1}{n} \sum_{j=1}^n \frac{a_{ij}}{\sum_i^n a_{ij}}, i, j = 1, 2, \dots, n$$

Step 4: Calculating Consistency Ratio (CR)

CR should be less than 0.1 for providing consistency. To find CI for AHP, the formulas below should be followed;

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

$$CR = \frac{CI}{RI}$$

3.2 GRA

GRA was introduced in 1982 by J. L. Deng and is one of the sub-titles of Systems Theory (Deng et al., 2021). In Control Theory, colors are often used to show the clarity of information. So, for completely known information, white is used, Gray for partially known information, and Black for completely unknown information (Wen et al., 2022). Briefly, the steps of GRA are given below.

Step 1: Creating the Decision Matrix

m: alternatives & each alternative has n criteria for evaluation (i: the row & j: the columns)

$$x_i = \{x_i(j), \dots, x_i(n)\} \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n \quad (1)$$

Step 2: Normalization

Since the criteria are measured differently, normalization is done to make them comparable. In this process, one of the criteria of more significant value better, small value better, or optimal value is selected, and one of the following 2,3,4 equations is used for all of them.

$$x_i^* = \frac{x_i(j) - \min_j x_i(j)}{\max_j x_i(j) - \min_j x_i(j)} \quad (\text{if bigger value is better}) \quad (2)$$

$$x_i^* = \frac{\max_j x_i(j) - x_i(j)}{\max_j x_i(j) - \min_j x_i(j)} \quad (\text{if small value is better}) \quad (3)$$

$$x_i^* = \frac{|x_i(j) - x_{ob}(j)|}{\max_j x_i(j) - x_{ob}(j)} \quad (\text{if optimal value is better}) \quad (4)$$

Step 3: Creating the Standardized Decision Matrix and Reference Series

Reference series are obtained from the normalization matrix. Provides the useful indicator x_0 (j) on Equation 5.

$$x_0 = \{x_0(j), \dots, x_0(n)\} \quad j = 1, 2, \dots, n \quad (5)$$

Then, the comparison matrix is obtained by adding the reference series to the decision matrix.

Step 4: Creating the Absolute Value Matrix

To find absolute values between x_0^* and x_i^* are calculated by using Equation 6.

$$\Delta = |x_0^*(j) - x_i^*(j)| \quad i = 1, 2, \dots, m \text{ and } j = 1, 2, \dots, n \quad (6)$$

Step 5: Calculating Gray Relationship Coefficients

Equation 7,8,9 are used to calculate Gray Relationship Coefficients

$$\gamma_{0i}(j) = \frac{\Delta_{min} + \xi \Delta_{max}}{\Delta_{0i}(j) + \xi \Delta_{max}} \quad (7)$$

$$\Delta_{max} = \max_i \max_j \Delta_{0i}(j) \quad (8)$$

$$\Delta_{min} = \min_i \min_j \Delta_{0i}(j) \quad (9)$$

In Equation 7, the parameter ζ represents the discriminant coefficient. It means that the value is $0 \leq \zeta \leq 1$ and the smaller ζ , the higher the distinguishability. This value is usually taken as $\zeta = 0.5$ to provide good stability and moderate discrimination (He et al., 2022).

Step 6: Calculating Gray Relationship Degree

The gray relational rating calculation is calculated using different equations if the criteria have equal weights and different weights. Equation 10 is used for equal weights, and Equation 11 is used for different weights.

$$\Gamma_{0i} = \frac{1}{n} \sum_{j=1}^n \gamma_{0i}(j) \tag{10}$$

$$\Gamma_{0i} = \frac{1}{n} \sum_{j=1}^n w_i(j) \gamma_{0i}(j) \tag{11}$$

In the following section, implementation and results are given.

4. Implementation and Results

As mentioned before, AHP and GRA methods are used in this study. First, to determine the weights of critical factors, AHP is used as explained below.

3.3 AHP Implementation

In the implementation of AHP, there are 7 critical factors and 5 experts. These experts know I4.0 and OPEX methodologies in manufacturing industries. The detailed characteristics of experts are given in Table 2.

Table 2. Characteristics of Experts

Expert	Position	Key Responsibilities	No. of working years
Expert 1	Operational Excellence Manager	Operational excellence control in operations	15
Expert 2	Lean Engineer	Lean process control in operations	7
Expert 3	Business Development Director	Work for solution-oriented to develop products and develop business	12
Expert 4	R&D Engineer	Work to reduce costs and waste and provide more output with the existing system	6
Expert 5	Operations Manager	Manage the whole operations	9

In the AHP implementation, the experts used Saaty's comparison scale (Saaty, 2008). After receiving each expert's opinion, the pairwise matrix for the critical factors is created by taking the geometric mean as seen in Table 3.

Table 3. The Pairwise Matrix for The Critical Factors

Critical Factors	CF1	CF2	CF3	CF4	CF5	CF6	CF7
CF1	1.00	0.50	0.16	1.02	0.25	0.33	0.35
CF2	2.00	1.00	2.00	3.00	2.00	0.20	0.33
CF3	6.12	0.50	1.00	2.00	0.33	2.00	2.00
CF4	0.98	0.33	0.50	1.00	1.15	0.33	0.50
CF5	4.08	0.50	3.00	0.87	1.00	2.00	2.00
CF6	0.33	0.20	2.00	0.33	0.50	1.00	0.50
CF7	0.35	0.33	2.00	0.50	0.50	0.50	1.00

The criteria weights obtained by dividing the value of each cell by the column total after the comparison matrix created after the pairwise comparisons and by taking the arithmetic average of the normalization matrix and row totals are obtained as seen in Table 4.

Table 4. Normalized Matrix and Weights of Critical Factors

Critical Factors	CF1	CF2	CF3	CF4	CF5	CF6	CF7	Weights
CF1	0.07	0.15	0.02	0.12	0.04	0.05	0.05	0.07
CF2	0.13	0.30	0.19	0.34	0.35	0.03	0.05	<u>0.20</u>
CF3	0.41	0.15	0.09	0.23	0.06	0.31	0.30	<u>0.22</u>
CF4	0.07	0.10	0.05	0.11	0.20	0.05	0.07	0.09
CF5	0.27	0.15	0.28	0.10	0.17	0.31	0.30	<u>0.23</u>
CF6	0.02	0.06	0.19	0.04	0.09	0.16	0.07	0.09
CF7	0.02	0.10	0.19	0.06	0.09	0.08	0.15	0.10

As seen in Table 4, the CF5, Infrastructure for Right Methodology, Techniques and Tools, is in the first place, the CF3, Organizational Strategy, is in the second place. At the same time, the third highest critical factor is Capital Investment (CF2). After the weights were determined, consistency analysis was conducted to see if the experts gave consistent answers during

pairwise comparisons. The consistency ratio calculated as a result of the analysis was less than 0.06, that is, 0.10, showing that consistency was achieved in the paired comparisons.

3.4 GRA Implementation

After finding the weights of the critical factors with the help of AHP, it is desired to analyse which of the 3 important manufacturing industries determined by the GRA method is in a better condition according to critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries. As mentioned before, these sectors have been determined as automotive, textile and food in terms of being the sectors that OPEX methodologies should be adopted in an integrated manner with I4.0 and directing the manufacturing industry. Therefore, the GRA implementation covers 3 alternative sectors based on 7 critical factors weighted by AHP.

While creating the decision matrix, it is necessary to evaluate according to 7 critical factors to determine the best among the alternative sectors. For this purpose, evaluation is made with 3 experts from each sector, a total of 9 experts. These experts know OPEX methodologies and I4.0 in their industries. The average decision matrix formed as a result of the evaluations taken from the experts is presented in Table 5.

Table 5. Average Decision Matrix of Experts

<i>Max and Min Decision</i>	<i>Max</i>	<i>Min</i>	<i>Max</i>	<i>Max</i>	<i>Max</i>	<i>Max</i>	<i>Max</i>
CFs							
Alternatives	CF1	CF2	CF3	CF4	CF5	CF6	CF7
Textile	7	4	7	3	5	4	5
Food	5	3	4	7	4	3	4
Automotive	5	4	7	8	5	4	7

As shown in Table 5, calculations are made by following the GRA steps and considering the minimum and maximum states of the critical factors. Except for the CF₂ critical factor, capital investment, other critical factors are required to be maximum. The criteria weights found with AHP are also included in the implementation. The strategic alignment between OPEX methodologies and I4.0 technologies for 3 alternative manufacturing industries according to 7 critical factors is obtained as in Table 6.

5% Decrease in Weights	0.067	0.190	0.209	0.086	0.219	0.086	0.095	GRA Degree	Rank
Alternatives/Critical Factors	CF1	CF2	CF3	CF4	CF5	CF6	CF7		
Textile	1.00	0.33	1.00	0.33	1.00	1.00	0.43	0.71	2
Food	0.33	1.00	0.33	0.71	0.33	0.33	0.33	0.48	3
Automotive	0.33	0.33	1.00	1.00	1.00	1.00	1.00	0.78	1
10% Decrease in Weights	0.063	0.180	0.198	0.081	0.207	0.081	0.090	GRA Degree	Rank
Alternatives/Critical Factors	CF1	CF2	CF3	CF4	CF5	CF6	CF7		
Textile	1.00	0.33	1.00	0.33	1.00	1.00	0.43	0.67	2
Food	0.33	1.00	0.33	0.71	0.33	0.33	0.33	0.45	3
Automotive	0.33	0.33	1.00	1.00	1.00	1.00	1.00	0.74	1
30% Decrease in Weights	0.049	0.140	0.154	0.063	0.161	0.063	0.070	GRA Degree	Rank
Alternatives/Critical Factors	CF1	CF2	CF3	CF4	CF5	CF6	CF7		
Textile	1.00	0.33	1.00	0.33	1.00	1.00	0.43	0.52	2
Food	0.33	1.00	0.33	0.71	0.33	0.33	0.33	0.35	3
Automotive	0.33	0.33	1.00	1.00	1.00	1.00	1.00	0.57	1
50% Decrease in Weights	0.035	0.100	0.110	0.045	0.115	0.045	0.050	GRA Degree	Rank
Alternatives/Critical Factors	CF1	CF2	CF3	CF4	CF5	CF6	CF7		
Textile	1.00	0.33	1.00	0.33	1.00	1.00	0.43	0.37	2
Food	0.33	1.00	0.33	0.71	0.33	0.33	0.33	0.25	3
Automotive	0.33	0.33	1.00	1.00	1.00	1.00	1.00	0.41	1

The cases where the AHP weights could increase or decrease by 5, 10, 30 and 50 percent, respectively, are evaluated. Even if the experts' opinions on the AHP implementation change by 50 percent, there is no variability in the results of the GRA implementation. It shows that this implementation is robust.

4. Discussions

OPEX is an inclusive management system that can effectively use the workforce, processes and technology to achieve sustainable success, provides leadership at all levels, and strengthens decision-making mechanisms (Jengwa & Pellisier, 2022). Strategic alignment between I4.0 technologies and OPEX methodologies provides many benefits such as reducing production costs, reducing stocks, reducing personnel circulation, and increasing customer satisfaction (Caiado et al., 2022).

From the sectoral perspective, in the evaluation made according to the determined criteria, the automotive sector was found to be in the best condition among 3 alternative sectors in terms of providing strategic alignment between OPEX methodologies and I4.0 technologies for

manufacturing industries. The automotive sector is one of the sectors where smart manufacturing applications are adopted the fastest under the I4.0 concepts (Gajdzik & Wolniak, 2022). When the studies on OPEX and I4.0 are examined, it is suggested that the strategic alignment between the two concepts is the primary expression of success in the global competition in the automotive industry (Wankhede & Vinodh, 2022). In particular, it is seen that the number of errors in operational processes has been reduced, and production excellence has improved with the developments in production innovations and production intelligence technologies (Javaid et al., 2022).

According to our results, in contrast with the automotive industry, the food industry is the worst among the 3 alternative sectors in terms of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries. The food sector has undergone radical changes due to its complex and multi-stakeholder structure, the increase in the human population and the increase in the demand in the market with this increasing population (Adimuthu et al., 2022). The food industry is highly competitive, and access to real-time data and waste minimization are the most important issues for this industry (Amaral & Orsato, 2022). In the food industry, I4.0 ensures a more flexible product that can be traced along the production chain. Machines can work together, adapt more quickly to changing the characteristics of the product and provide bespoke production products for each customer. At the same time, integrating these processes with OPEX methodologies simplifies production processes, and minimizes waste and operational errors.

OPEX methodologies and I4.0 technologies for manufacturing industries have been determined as the worst among the 3 alternative sectors in this study. The food sector has undergone radical changes due to its complex and multi-stakeholder structure, the increase in the human population and the increase in the demand in the market with this increasing population. With this perspective, providing strategic alignment between OPEX methodologies and I4.0 technologies in the food industry is extremely important. For this reason, managers must develop strategies and policies regarding I4.0 and OPEX applications in production processes.

5. Implications and Framework Development

According to the results, implications for managers are proposed to provide strategic alignment between OPEX and I4.0 technologies in smart manufacturing.

Implication 1: Educated and Knowledgeable Employee

When focusing on critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries, it can be seen that CF₅, Infrastructure for Right Methodology, Techniques and Tools, is in the first place. It is essential to provide the appropriate infrastructure and to match the right I4.0 practices with the right methods to ensure strategic alignment between OPEX methodologies and I4.0, especially in the manufacturing industries. Educated and knowledgeable employees are needed to match appropriate techniques with the right technologies. For this reason, training on the subject should be organized and qualified personnel should be trained. In addition, an analysis should be made to determine which I4.0 technology is needed in which process. When the correct OPEX methodologies are integrated with the analyses made, results should be checked continuously and aim to reach the most efficient result.

Implication 2: Following new trends in smart manufacturing

Moreover, CF₃, Organizational Strategy, which was determined as the second most crucial criterion, was determined as more important than other criteria. The reason for this is that no matter how much information sharing, employee involvement and other criteria, when the corporate culture has a flexible and non-innovative structure, it does not adopt I4.0 applications and OPEX methodologies as an organizational strategy, does not volunteer to put the strategies into practice. For this reason, organizations should always follow the new strategy and adopt the recent trends in manufacturing. One of the most important ways to ensure corporate sustainability in a competitive environment is to follow new technologies and be willing to apply them in production processes.

Implication 3: Effective planning of investments

In addition, capital investment (CF₂) is the third important factor for strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries. In addition to other criteria expected to be at high levels, it is crucial to always get the highest result with the lowest cost and investment in the manufacturing industries. For this reason, accurate and effective investment planning should be ensured by making analyses to keep the capital investments at the lowest level for strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries.

5. Conclusions

OPEX is needed in technology-focused, rapidly changing business models that require organizations to undergo an end-to-end business transformation. Moreover, companies gain numerous advantages and have a chance of sustainable growth despite challenging competitive conditions by adopting OPEX methodologies. In addition, I4.0 is critical in accelerating the adoption of OPEX methodologies, particularly approaches such as lean management and 6 Sigma, and providing companies with more resource opportunities. Therefore, strategic alignment between OPEX methodologies and I4.0 technologies is an issue that needs to be addressed for the sustainability of the sectors and operational improvements.

In particular, manufacturing industries, especially in automotive, food, textile etc. which are essential for national economies, need to attach importance to the adoption of OPEX methodologies and the I4.0 technologies that trigger these methodologies to achieve operational improvement. In today's competitive environment, sustainability, waste minimization, and simplicity come to the fore besides producing good products. Hence, this study aims to determine the critical factors of strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries by using AHP and comparative analyses between automotive, food, and textile industries in terms of strategic alignment between OPEX methodologies and I4.0 technologies by using GRA.

According to the results of this study, the CF5, Infrastructure for Right Methodology, Techniques and Tools, is determined as the most important factor for strategic alignment between OPEX methodologies and I4.0 technologies for manufacturing industries and based on GRA results, the automotive industry is determined as the best alternative in terms of strategic alignment between OPEX methodologies and I4.0 technologies.

As a limitation of the study, since OPEX methodologies and I4.0 technologies are not fully applied in every manufacturing industry, the number of experts who know about establishing the relationship between these two concepts is very low. The number of sectors to be compared can be increased for further research. In addition, the implementation can be customized for developing or developed countries.

References

- Adimuthu, R., Muduli, K., Ray, M., Singh, S., & Ahmad, T. S. T. (2022). Exploring Role of Industry 4.0 Techniques for Building a Promising Circular Economy Concept: Manufacturing Industry Perspective. In *Machine Learning Adoption in Blockchain-Based Intelligent Manufacturing* (pp. 111-124). CRC Press.
- Amaral, D. G., & Orsato, R. J. (2022). Digital platforms for food waste reduction: The value for business users. *Business Strategy and the Environment*. DOI: 10.1002/bse.3193
- Antony, J., McDermott, O., Powell, D., & Sony, M. (2022). The evolution and future of lean Six Sigma 4.0. *The TQM Journal*, (ahead-of-print).
- Bagnoli, C., Albarelli, A., Biazzo, S., Biotto, G., Marseglia, G. R., Massaro, M., ... & Troiano, L. (2022). The Integration of Digital Business Models: The Amazon Case Study. In *Digital Business Models for Industry 4.0* (pp. 211-239). Springer, Cham.
- Benítez, J., Delgado-Galván, X., Izquierdo, J., & Pérez-García, R. (2012). Improving consistency in AHP decision-making processes. *Applied Mathematics and Computation*, 219(5), 2432-2441.
- Bhat, S., Antony, J., Gijo, E. V., Koul, R., Cudney, E. A., & Chakraborty, A. (2022). A study on critical failure factors of Design for Six Sigma in Indian companies: results from a pilot survey. *The TQM Journal*, (ahead-of-print).
- Buer, S. V., Strandhagen, J. O., & Chan, F. T. (2018). The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda. *International Journal Of Production Research*, 56(8), 2924-2940.
- Caiado, R. G. G., Scavarda, L. F., Azevedo, B. D., de Mattos Nascimento, D. L., & Quelhas, O. L. G. (2022). Challenges and benefits of sustainable industry 4.0 for operations and supply chain management—A framework headed toward the 2030 agenda. *Sustainability*, 14(2), 830.
- Caiado, R. G. G., Scavarda, L. F., Azevedo, B. D., de Mattos Nascimento, D. L., & Quelhas, O. L. G. (2022). Challenges and benefits of sustainable industry 4.0 for operations and supply chain management—A framework headed toward the 2030 agenda. *Sustainability*, 14(2), 830.
- Carvalho, M., Sá, J. C., Marques, P. A., Santos, G., & Pereira, A. M. (2022). Development of a conceptual model integrating management systems and the Shingo Model towards operational excellence. *Total Quality Management & Business Excellence*, 1-24.
- Castelo-Branco, I., Cruz-Jesus, F., & Oliveira, T. (2019). Assessing Industry 4.0 readiness in manufacturing: Evidence for the European Union. *Computers in Industry*, 107, 22-32.

- Charro, A., & Schaefer, D. (2018). Cloud Manufacturing as a new type of Product-Service System. *International Journal of Computer Integrated Manufacturing*, 31(10), 1018-1033.
- Deng, J., Yan, Q., Lu, J., Xiong, Q., & Pan, J. (2021). Optimisation of Lapping Process Parameters for Single-Crystal 4H-SiC Using Orthogonal Experiments and Grey Relational Analysis. *Micromachines*, 12(8), 910.
- Dev, N. K., Shankar, R., & Qaiser, F. H. (2020). Industry 4.0 and circular economy: Operational excellence for sustainable reverse supply chain performance. *Resources, Conservation and Recycling*, 153, 104583.
- Found, P., Lahy, A., Williams, S., Hu, Q., & Mason, R. (2018). Towards a theory of operational excellence. *Total Quality Management & Business Excellence*, 29(9-10), 1012-1024.
- Gajdzik, B., & Wolniak, R. (2022). Smart Production Workers in Terms of Creativity and Innovation: The Implication for Open Innovation. *Journal of Open Innovation: Technology, Market, and Complexity*, 8(2), 68.
- Grandinetti, R., Ciasullo, M. V., Paiola, M., & Schiavone, F. (2020). Fourth industrial revolution, digital servitization and relationship quality in Italian B2B manufacturing firms. An exploratory study. *The TQM Journal*.
- Grillo, H., Alemany, M. M. E., & Caldwell, E. (2022). Human resource allocation problem in the Industry 4.0: A reference framework. *Computers & Industrial Engineering*, 169, 108110.
- Gupta, S., S. Modgil, and A. Gunasekaran. (2020). Big Data in Lean six Sigma: A Review and Further Research Directions. *International Journal of Production Research* 58 (3): 947–969.
- Hassoun, A., Aït-Kaddour, A., Abu-Mahfouz, A. M., Rathod, N. B., Bader, F., Barba, F. J., ... & Regenstein, J. (2022). The fourth industrial revolution in the food industry—Part I: Industry 4.0 technologies. *Critical Reviews in Food Science and Nutrition*, 1-17.
- He, L., Tang, X., Luo, Q., Liao, Y., Luo, X., Liu, J., ... & Li, Y. (2022). Structure optimization of a heat pipe-cooling battery thermal management system based on fuzzy grey relational analysis. *International Journal of Heat and Mass Transfer*, 182, 121924.
- Jaskó, S., Skrop, A., Holczinger, T., Chován, T., & Abonyi, J. (2020). Development of manufacturing execution systems in accordance with Industry 4.0 requirements: A review of standard-and ontology-based methodologies and tools. *Computers in industry*, 123, 103300.
- Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2022). Enabling flexible manufacturing system (FMS) through the applications of industry 4.0 technologies. *Internet of Things and Cyber-Physical Systems*.

- Jengwa, E., & Pellissier, R. (2022). An operational excellence strategy implementation model for growth in a volatile, uncertain, complex, and ambiguous environment. *Acta Commercii*, 22(1), 11.
- Karaaslan, A., Adar, T., & Delice, E. K. (2022). Regional evaluation of renewable energy sources in Turkey by new integrated AHP-MARCOS methodology: a real application. *International Journal of Sustainable Energy*, 41(2), 103-125.
- Kaswan, M. S., Rathi, R., Garza-Reyes, J. A., & Antony, J. (2022). Green lean six sigma sustainability-oriented project selection and implementation framework for manufacturing industry. *International Journal of Lean Six Sigma*, (ahead-of-print).
- Keivanpour, S. (2022). Lean and Industry 4.0 Implication in Circular Design: An Operational Performance Perspective. In *Approaches, Opportunities, and Challenges for Eco-design 4.0* (pp. 55-66). Springer, Cham.
- Kharub, M., Mor, R. S., & Rana, S. (2022). Mediating role of manufacturing strategy in the competitive strategy and firm performance: evidence from SMEs. *Benchmarking: An International Journal*.
- Krstić, M., Agnusdei, G. P., Miglietta, P. P., Tadić, S., & Roso, V. (2022). Applicability of Industry 4.0 Technologies in the Reverse Logistics: A Circular Economy Approach Based on COmprehensive Distance Based RAnking (COBRA) Method. *Sustainability*, 14(9), 5632.
- Kumar, M., & Singh, K. (2022). Fuzzy fault tree analysis of chlorine gas release hazard in Chlor-Alkali industry using α -cut interval-based similarity aggregation method. *Applied Soft Computing*, 125, 109199.
- Luz Tortorella, G., Cauchick-Miguel, P. A., Li, W., Staines, J., & McFarlane, D. (2022). What does operational excellence mean in the Fourth Industrial Revolution era?. *International Journal of Production Research*, 60(9), 2901-2917.
- Madhavika, W. D. N. (2021). A Study on Operational Excellence: Sustainable Supply Chains of Manufacturing Industries during COVID-19 Pandemic. *Proceedings of Peradeniya University International Research Sessions*.
- Mahmat, Z., Sua, L. S., & Balo, F. (2022). Evaluating Alternatives in Dental Implant Materials by SWARA and Gray Relational Analysis. In *Mitigating Climate Change* (pp. 221-233). Springer, Cham.
- Miandar, T., Galeazzo, A., Furlan, A. (2020). Coordinating Knowledge Creation: A Systematic Literature Review on the Interplay Between Operational Excellence and Industry 4.0 Technologies. In: Bettiol, M., Di Maria, E., Micelli, S. (eds) *Knowledge Management and Industry 4.0. Knowledge Management and Organizational Learning*, vol 9. Springer, Cham. https://doi.org/10.1007/978-3-030-43589-9_6

- Muazu, M. H., Tasmin, R., & Javaid, M. (2021). Operational excellence, regulatory framework and firm characteristics in the oil sector: the role of enterprise risk management implementation. *International Journal of Services and Operations Management*, 38(4), 490-507.
- Muhammad, N., Upadhyay, A., Kumar, A., & Gilani, H. (2022). Achieving operational excellence through the lens of lean and Six Sigma during the COVID-19 pandemic. *The International Journal of Logistics Management*.
- Nayak, R., & Choudhary, S. (2022). Operational excellence in humanitarian logistics and supply chain management through leagile framework: A case study from a non-mature economy. *Production Planning & Control*, 33(6-7), 606-621.
- Nhelekwa, L. B., Mollel, J. Z., & Taifa, I. W. (2022). Assessing the digitalisation level of the Tanzanian apparel industry: Industry 4.0 perspectives. *Research Journal of Textile and Apparel*, (ahead-of-print).
- Psarommatis, F., Sousa, J., Mendonça, J. P., & Kiritsis, D. (2022). Zero-defect manufacturing the approach for higher manufacturing sustainability in the era of industry 4.0: A position paper. *International Journal of Production Research*, 60(1), 73-91.
- Ramadan, M. A., Al Dhaheri, M. K., Maalouf, M., Antony, J., Bhat, S., & Gijo, E. V. (2022). Application of Six Sigma methodology to enhance the productivity and performance of a hotel in the UAE. *The TQM Journal*.
- Ramadan, M. A., Al Dhaheri, M. K., Maalouf, M., Antony, J., Bhat, S., & Gijo, E. V. (2022). Application of Six Sigma methodology to enhance the productivity and performance of a hotel in the UAE. *The TQM Journal*.
- Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International journal of services sciences*, 1(1), 83-98.
- Saaty, T. L., & Vargas, L. G. (2012). The seven pillars of the analytic hierarchy process. In *Models, methods, concepts & applications of the analytic hierarchy process* (pp. 23-40). Springer, Boston, MA.
- Sassanelli, C., Arriga, T., Zanin, S., D'Adamo, I., & Terzi, S. (2022). Industry 4.0 Driven Result-oriented PSS: An Assessment in the Energy Management. *International Journal of Energy Economics and Policy*, 12(4), 186-203.
- Surianarayanan, G., & Menkhoff, T. (2020). Outcomes of an expert survey: Are Singapore's manufacturing small and medium enterprises ready to embrace industry 4.0. 19th International WWW/Internet Conference ICWI 2020: November 18-20, Virtual: Proceedings, 51-60.

- Tissir, S., Cherrafi, A., Chiarini, A., Elfezazi, S., & Bag, S. (2022). Lean Six Sigma and Industry 4.0 combination: Scoping review and perspectives. *Total Quality Management & Business Excellence*, 1-30.
- Tissir, S., Cherrafi, A., Chiarini, A., Elfezazi, S., & Bag, S. (2022). Lean Six Sigma and Industry 4.0 combination: Scoping review and perspectives. *Total Quality Management & Business Excellence*, 1-30.
- Topno, A. R., Job, M., Rusia, D. K., Kumar, V., Bharti, B., & Singh, S. D. (2022). Prioritization and identification of vulnerable sub-watersheds using morphometric analysis and integrated AHP-VIKOR method. *Water Supply*.
- Trakulsunti, Y., Antony, J., Jayaraman, R., & Tortorella, G. (2022). The application of operational excellence methodologies in logistics: a systematic review and directions for future research. *Total Quality Management & Business Excellence*, 1-20.
- Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A. K., Saraswat, S., Sharma, S., Li, C., ... & Georgise, F. B. (2022). A Novel Smart Production Management System for the Enhancement of Industrial Sustainability in Industry 4.0. *Mathematical Problems in Engineering*, 2022.
- Veisi, H., Deihimfard, R., Shahmohammadi, A., & Hydarzadeh, Y. (2022). Application of the analytic hierarchy process (AHP) in a multi-criteria selection of agricultural irrigation systems. *Agricultural Water Management*, 267, 107619.
- Virmani, N., & Salve, U. R. (2021). Significance of Human Factors and Ergonomics (HFE): Mediating Its Role Between Industry 4.0 Implementation and Operational Excellence. *IEEE Transactions on Engineering Management*.
- Wahab, M. H. A. A. A., Ibrahim, N., Yaacob, A. A., Ismail, M., Muhayiddin, M. N., Ab Rahman, S. M., & Osman, A. A. (2022). Exploring the Success Factors of Operational Excellence in SMEs Manufacturing Sectors. *International Journal of Academic Research in Business and Social Sciences*.
- Wankhede, V. A., & Vinodh, S. (2022). Benchmarking Industry 4.0 readiness evaluation using fuzzy approaches. *Benchmarking: An International Journal*.
- Wen, P., Li, L., Xue, H., Jia, Y., Gao, L., Li, R., & Huo, L. (2022). Comprehensive evaluation method of the poultry house indoor environment based on gray relation analysis and analytic hierarchy process. *Poultry Science*, 101(2), 101587.
- Yu, D., & Hong, X. (2022). A theme evolution and knowledge trajectory study in AHP using science mapping and main path analysis. *Expert Systems with Applications*, 117675.

Zhang, M., Zhao, H., Fan, L., & Yi, J. (2022). Dynamic modulus prediction model and analysis of factors influencing asphalt mixtures using gray relational analysis methods. *Journal of Materials Research and Technology*.