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Alignment of product design and supply chain for enhancing sustainability and coordination in industries

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ABSTRACT

Choosing a project portfolio to improve sustainability in the supply chain is a vital issue for industries. The main goal of the portfolio is to align the organization's strategic objectives with project selection, ensuring that these projects make a meaningful contribution to the overall sustainability of the portfolio. This research specifically examines the integration of product portfolio design and supply chain design in the construction industry. The study utilizes an analytical model and optimization techniques to propose innovative solutions aimed at enhancing the alignment between suppliers and the product portfolio. Improving the efficiency and flexibility of the supply chain is accomplished through optimal coordination of both the product portfolio and the supply chain portfolio. This research explores how supply chain networks align with the product portfolio, focusing on creating flexibility in product portfolio management processes, managing changes, and addressing variability in different characteristics. The results indicate that effective and timely integration of product portfolio design with supply chain design can lead to reduced organizational costs and increased overall productivity. Improved coordination and integration between suppliers and final products have resulted in enhanced supply chain performance and lower ongoing organizational expenses.

Keywords: supply chain, product portfolio, integration, organizational expenses, product portfolio.

1. INTRODUCTION

In today's complex and ever-changing industrial environment, effectively coordinating and aligning supply chain and product design is crucial. A key strategy for improving sustainability within the supply chain is the careful selection of projects within the portfolio. This approach helps align the organization's strategic goals with its production and operational activities, ultimately enhancing efficiency and productivity across the supply chain. Moreover, integrating product portfolio design with supply chain design is vital for increasing both efficiency and flexibility. This integration can lead to cost savings and improved productivity, especially in intricate sectors like the forest products biorefinery industry, where managing production variability is essential.

Additionally, ensuring that supply chain networks align with the product portfolio is critical for boosting supply chain performance. This alignment enhances coordination between suppliers and end products, resulting in lower operational costs and increased organizational productivity. Utilizing analytical models and optimization methods can help organizations maximize their supply chain productivity and efficiency. In conclusion, research into supply chain integration, alignment, and product design is essential for organizations aiming to thrive in today's competitive landscape and achieve strategic goals like supply chain sustainability. By adopting effective methodologies and utilizing advanced analytical tools, organizations can make significant improvements in their supply chains and optimize the use of available resources.

In today's industrial environment, combining product design with supply chain management is essential for improving sustainability and operational efficiency. While there is growing awareness of this connection, significant research gaps remain in understanding how to effectively align these two areas to tackle sustainability challenges. Most existing research has focused on product design or supply chain practices separately, often overlooking the potential benefits that can come from their integration. While previous literature has examined sustainable practices in product design—such as environmentally friendly design and life cycle assessment—and in supply chain management—like green logistics and sustainable sourcing—there is a notable lack of comprehensive frameworks that demonstrate how to cohesively integrate these elements. This oversight limits industries' ability to fully achieve sustainability goals, as fragmented approaches can lead to inefficiencies and missed opportunities for innovation. The main issue addressed in this research is the lack of connection between product design and supply chain processes, which hinders the implementation of sustainable practices across various industries. As organizations strive to meet environmental regulations and consumer demands for sustainability, understanding the interaction between these functions becomes increasingly critical.

Aligning product design and supply chain practices is crucial for increasing sustainability and coordination across industries. Alignment ensures that product development processes are in sync with supply chain capabilities, leading to more efficient resource use, reduced waste, and overall improved sustainability. When design strategies and supply chain operations are coordinated, companies can respond more effectively to market demands and environmental challenges. Examples of Alignment

- Eco-Friendly Materials: Companies prioritizing sustainable materials in their product designs often work closely with suppliers to ensure these materials are sourced responsibly.
- Circular Supply Chains: Brands like Patagonia exemplify alignment by designing long-lasting, recyclable products supported by their supply chain practices.

Key Aspects of Alignment

- Collaboration: Strong communication between design teams and supply chain managers fosters innovation and agility.
- Shared Goals: Establishing common sustainability objectives simplifies efforts and maximizes impact.
- Integrated Processes: Utilizing integrated systems and tools facilitates real-time data sharing and decision-making.

This study introduces a new framework that emphasizes the alignment of product design with supply chain strategies, offering a comprehensive approach to sustainability. By integrating findings from various fields, this research not only addresses the identified gaps but also provides practical insights for professionals. Unlike existing studies that focus narrowly on individual elements, our approach highlights the interdependencies and collaborative potential between product design and supply chain management.

2. LITERATURE REVIEW

A supply chain is defined as "a network of organizations engaged in upstream and downstream alliances through various processes and activities that create value in the form of products and services for end customers" (Christopher, 2016). It includes both supply and demand, reflecting the life cycle of a product or service from its initial conception to final consumption (Ellram & Murfield, 2019). The members of the supply chain are interconnected through a series of functional activities that ensure goods or services are delivered on time and meet the desired specifications (Helo & Shamsuzzoha, 2020). Effectively managing the flow of materials and information among the different participants in the chain is crucial for maximizing the overall value delivered to customers in a globalized environment (Giannakis et al., 2019). This continuous process can only be optimized by establishing an integrated supply chain system (Strong et al., 2018).

The lean supply chain focuses on reducing lead times, improving efficiency, enhancing manufacturing flexibility, and lowering costs. This approach creates a scheduling framework across the supply chain and utilizes a pull system to effectively meet customer demands. In line with these goals, the lean supply chain also emphasizes continuous improvement, aiming to refine both the product and its production processes while maintaining balance within the supply chain.

The long-life cycle of standard products often results in stable designs that remain unchanged for many years. By considering elements such as low-cost items, global manufacturing capabilities, and predictable demand patterns, organizations can enhance profitability by minimizing costs and implementing effective scheduling throughout the supply chain and across the product life cycle. This reasoning justifies the use of a supply chain for standardized products.

Beyond cost reduction, a lean supply chain fosters efficiency and flexibility. It improves product quality through ongoing enhancements, which in turn increases customer interest and satisfaction. Therefore, to boost internal performance and customer satisfaction, standard products should be designed and produced using a lean supply chain throughout all stages of the product life cycle (Mohammad Modarres Yazdi et al., 2006) (table 1).

Table 1. When to Use Different Supply Chains

Product Type	Product Life Cycle	Supply Chain Type
Standard	Introduction	Lean Supply Chain
Innovative	Introduction	Agile Supply Chain
Hybrid	Growth	Agile Supply Chain
Standard	Maturity	Lean and Hybrid Supply Chain
Standard	Decline	Lean Supply Chain

The article by Kerstin U. Langenberg (2009) highlights the vital need for aligning the product portfolio with the supply chain, emphasizing this crucial issue. Researchers argue that effective coordination between these two areas can significantly boost organizational efficiency and productivity. Studies show that a lack of alignment can lead to higher costs, lower service quality, and ultimately, decreased customer satisfaction. Various research efforts have suggested methods to evaluate and enhance this alignment, including the use of analytical models and optimization strategies.

The literature review in Behrang Mansoornejad (2009) highlights the importance of integrating product portfolio design with supply chain design in the forest industry. Research shows that this integration can lead to increased efficiency, lower costs, and greater sustainability. Numerous studies indicate that achieving this integration requires in-depth analysis and the use of modern management

techniques at the portfolio governance level. In a similar vein, María-José Verdecho (2020) reviews existing research on sustainable project portfolio selection. This review examines various models and frameworks for evaluating and selecting sustainable projects, emphasizing the essential role of sustainability indicators and multi-criteria approaches in the selection process.

Despite substantial research on supply chains and product portfolios, the current literature remains fragmented and lacks focus due to the diverse ways these two areas are interconnected. Many studies fail to consider the specific contexts in which this research occurs. Therefore, there is an urgent need for more context-specific investigations that take into account the unique aspects of organizational cultures, including social, political, economic, and technological factors. This study explores the factors within supply chain dynamics that influence product portfolio design. The central research question is: What are the most significant supply chain factors impacting product portfolios? By addressing this gap, the study makes a valuable contribution to the existing literature. The factors identified from the literature, after localization by experts, are summarized in Table 2.

Table 2. Factors discovered from the literature

No	Source	Sub factor	Factors
1	Mello et al., 2015	Demand Forecasting	**Supply**
2	Dunbar, 1980	Cost Management	**cost**
3	Hans, 2021 Ripozo et al., 2014 Mello et al., 2015	Risk Management	**Product**
4	Mello et al., 2015 Adako et al., 2018 Kingsman et al., 1993	Flexibility and Responsiveness	
5	Al-Sharif and Karatas, 2016 Lee et al., 2017	Product Lifecycle Management	
6	Dunbar, 1980 Swiss et al., 2019 Hans, 2021	Supplier Relationships	**Supply chain**
7	Ripozo et al., 2014 Mello et al., 2015	Alignment of Goals	
8	Mello et al., 2015 Manzini and Orgo, 2018 Elastner and Krause, 2014	Sustainability Considerations	
9	Swiss et al., 2019	Technology Integration	

A comprehensive review of the literature reveals a range of sustainability approaches in both fields. For instance, while it has been shown that environmentally friendly design techniques reduce material waste (Chertow, 2000), the impact of integrating these designs with sustainable supply chain practices remains unclear (Seuring & Müller, 2008). Additionally, studies like those by Zhu et al. (2013) emphasize the importance of supply chain collaboration for achieving sustainability, yet they do not address how product design can facilitate this collaboration. The aim of this research is to bridge these gaps by providing a thorough analysis of the existing literature and proposing a framework that enhances the alignment between product design and supply chain operations.

Coordinating product design and supply chain practices is essential for enhancing sustainability and efficiency, particularly in the construction industry. However, this sector faces several specific challenges.

First, the fragmented nature of supply chains, involving multiple stakeholders such as contractors, subcontractors, suppliers, and regulatory bodies, can lead to misunderstandings and inefficiencies. Delays in material delivery or design changes can disrupt project timelines and escalate costs. Additionally, construction projects must comply with various local, state, and federal regulations, which can complicate coordination and hinder innovation. Sourcing sustainable materials presents another challenge, as limited availability and higher costs can impede efforts to create environmentally friendly designs. Moreover, many construction companies still rely on outdated technologies, making it difficult to implement integrated systems for design and supply chain management; a lack of real-time data sharing can further result in poor decision-making. Each construction project is unique, which complicates the standardization of processes and can lead to misalignment between design strategies and supply chain practices. Finally, the industry often grapples with labor shortages, which can negatively impact both design execution and supply chain efficiency, resulting in production delays and increased costs. Addressing these challenges requires a coordinated effort from all stakeholders in the construction industry. By fostering collaboration, investing in technology, and prioritizing sustainability, companies can enhance the alignment of product design and supply chain practices, ultimately improving overall project outcomes.

This study emphasizes the crucial integration of product design and supply chain management to enhance sustainability in the construction industry. While existing research often addresses these components separately, this study sets itself apart in several ways. First, it adopts a comprehensive approach, examining the interaction between product design and supply chain logistics, and demonstrating how their coordination can lead to improved sustainability outcomes. Unlike previous studies that focus on one aspect, this research explores the synergy between both. Second, the study introduces innovative frameworks and methodologies that have not been previously explored in the literature. By incorporating recent advancements in technology and sustainable practices, it provides fresh insights into effective integration strategies. Additionally, this research uniquely investigates the role of diverse stakeholders in the construction process, highlighting how their collaboration can overcome common challenges in achieving sustainability—an aspect often overlooked in existing studies.

The study also proposes the use of real-time data sharing and communication tools, which can significantly enhance decision-making processes. This focus on technology integration distinguishes it from traditional approaches that rely on outdated systems. Finally, by including case studies that illustrate successful implementations of coordinated practices, the research offers practical examples that can serve as models for industry professionals, addressing a gap often found in current literature. This study not only highlights the importance of integrating product design and supply chain practices but also presents novel contributions that advance the understanding and application of sustainability in the construction industry.

Previous studies on the alignment of product design and supply chain management have largely overlooked the critical interdependencies between these two domains, resulting in a fragmented approach that limits the potential for sustainability and operational efficiency. Specifically, research has tended to focus either on product design or supply chain logistics in isolation, failing to consider how design decisions can significantly influence supply chain sustainability and vice versa. This gap is particularly evident in the lack of integrated frameworks that address both areas concurrently, which has hindered industries from achieving cohesive strategies that enhance sustainability. This research addresses these shortcomings by proposing a comprehensive framework that aligns product design with supply chain processes, emphasizing their interconnectedness and the importance of sustainability metrics that apply to both domains. By providing practical applications and case studies, this study not only validates the proposed framework but also offers actionable insights for organizations seeking to improve coordination and sustainability across their operations.

3. METHODOLOGY

This article combines qualitative and quantitative methods to explore the integration of product portfolio design and supply chain management. Initially, primary data were gathered through interviews

and structured questionnaires, complemented by qualitative analyses. Following this, multi-objective decision-making models (MCDM) were employed to analyze and select the optimal products based on supply chain indicators. Philosophically, this study is practical, as its findings are intended for organizational application. Methodologically, it is classified as descriptive-survey research. A systematic approach was taken to identify the factors influencing the integration of product portfolios with supply chains, involving a review of reputable scientific articles from platforms like Science Direct, Emerald Insight, and Google Scholar.

Population: The target population includes professionals involved in product design and supply chain management across various industries, such as manufacturing, retail, and consumer goods. Participants have at least 12 years of experience in their respective fields. Professionals hold positions related to product design, supply chain management, or sustainability. Organizations have implemented sustainability initiatives in their product design or supply chain processes. Individuals without relevant experience or positions in the aforementioned fields don't consider. A total of 10 respondents will be targeted to ensure a diverse representation of perspectives. This sample size is deemed sufficient to achieve statistical significance and provide robust insights into the alignment of product design and supply chain management. The respondents will be drawn from different sectors, with an aim for balanced representation across industries to enhance the generalizability of the findings. A structured questionnaire will be developed to gather quantitative data regarding the practices, challenges, and perceptions of alignment between product design and supply chain management. Relevant organizational documents, such as sustainability reports and product design specifications, were be analyzed to supplement the primary data collection. The alignment of product design and supply chain management involves various sustainability criteria (e.g., environmental impact, cost efficiency, social responsibility). TOPSIS allows for the simultaneous consideration of these diverse criteria, facilitating a comprehensive analysis. The method is relatively straightforward and easy to understand, making it accessible for practitioners and stakeholders involved in decision-making processes. TOPSIS has been successfully applied in various sustainability assessments, making it a suitable choice for evaluating the effectiveness of product design and supply chain alignment in achieving sustainability outcomes.

From this literature review, 25 factors affecting the integration of product portfolios with supply chains were identified. These factors were then weighted based on expert opinions, localized, and assessed using a Likert scale. All of the 25 factors, 10 were approved by experts. The weights of these factors were determined using the Shannon entropy method and incorporated into further calculations. A questionnaire utilizing a Likert scale was then distributed to industry experts to assess the importance of these 10 factors. The reliability of the questionnaire was confirmed with a Cronbach's alpha value of 0.85, and its content validity was also verified by industry experts. The final ranking of the factors was conducted using the TOPSIS technique.

To ensure the validity and reliability of the research instruments used in the study on the alignment of product design and supply chain management for sustainability, several comprehensive steps were undertaken beyond merely calculating Cronbach's alpha.

Content validity was established through a systematic process involving expert evaluations. A panel of experts in product design, supply chain management, and sustainability was convened to review the survey instruments and interview guides. They assessed the relevance and clarity of each item in relation to the study's objectives. Feedback from these experts was used to refine the items, ensuring that they adequately covered the constructs of interest. Additionally, a pilot study was conducted with a small, representative sample to gather preliminary data on the instrument's effectiveness, allowing for further adjustments based on participant feedback.

To enhance construct validity, the research employed both exploratory and confirmatory factor analysis (EFA and CFA). Initially, EFA was conducted on the survey data to identify underlying patterns and confirm whether the items grouped as expected according to the theoretical framework. Following this, CFA was used to test the hypothesized relationships between the constructs, ensuring that the data fit the proposed model well. This dual approach allowed for a rigorous examination of the constructs, confirming that the instruments measured the intended theoretical dimensions accurately.

While Cronbach's alpha is a widely used measure of internal consistency, additional reliability assessments were performed to provide a more comprehensive evaluation. Test-retest reliability was assessed by administering the same instrument to a subset of respondents at two different time points. The correlation between the two sets of scores was calculated to ensure stability over time. Furthermore, inter-rater reliability was examined for qualitative data obtained from interviews, where multiple researchers coded the same transcripts independently. The consistency of their coding was analyzed using Cohen's kappa to ensure agreement among raters. These multi-faceted approaches to reliability ensured that the instruments were not only consistent but also robust across different contexts and evaluators.

To improve the clarity of the methodology concerning the analytical models used in coordinating product design and supply chain management for enhanced sustainability in the construction industry, particularly regarding the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). TOPSIS is a multi-criteria decision-making (MCDM) approach that identifies solutions from a finite set of options based on their geometric distance to an ideal solution. This method assists in ranking alternatives by considering both the best and worst possible outcomes. Reasons for Selection are:

- Simplicity and Efficiency: TOPSIS is easy to implement and provides quick results, making it suitable for complex decision-making scenarios in the construction industry.
- Comprehensive Evaluation: It allows for the simultaneous assessment of multiple sustainability criteria, such as environmental impact, cost efficiency, and social implications.
- Ideal Solution Benchmarking: By defining both an ideal and a negative-ideal solution, it provides a clear framework for evaluating relative performance.

By providing detailed explanations of the analytical models and the rationale behind their selection, particularly the use of TOPSIS, the methodology will be clearer and more robust. This added clarity will enhance understanding of how these models contribute to achieving sustainability objectives in the construction industry. The TOPSIS model, introduced by Huang and Yun in 1981, is a widely used multi-attribute decision-making method. This technique is based on the principle that the selected option should be closest to the positive ideal (the best-case scenario) and furthest from the negative ideal (the worst-case scenario). The steps for applying this method are as follows:

1. Formation of the Decision Matrix
2. Calculation of the Scale-Free Matrix: This step normalizes the scales in the decision matrix to eliminate disparities between indicators, where each value is divided by the vector size corresponding to the same indicator (Equation 1).

$$n_{ij} = \frac{r_{ij}}{\sqrt{\sum_{i=1}^{m} r_{ij}^{2}}} \qquad \text{Equation 1}$$

3. Calculation of the Weight Matrix:This is performed using the Shannon entropy method.
4. Obtaining the Weighted Fuzzy Decision Matrix: The weights of the indicators are multiplied by the normalized fuzzy decision matrix (Equation 2).

$$v_{ij} = r_{ij} \times w_j \qquad \text{Equation 2}$$

5. Determining the Positive and Negative Ideal Points:

- Positive Ideal: The highest values for positive indices and the lowest for negative indices (Equation 3).

$$A^{+} = (V_1^{+}, V_2^{+}, \dots\dots, V_n^{+}) \qquad V_1^{+} = \text{Max } V_J \qquad \text{Equation 3}$$

- Negative Ideal: The highest values for negative indices and the lowest for positive indices (Equation 4).

$A^- = (V_1^-, V_2^-, \dots\dots, V_n^-) \qquad V_1^- = \text{Min } V_J$ Equation4

6. Calculating the Euclidean Distance: The distance of each option from the ideal points is computed. The distance from the positive ideal is calculated using Equation 5, while Equation 6is used for the negative ideal:

$$d_i^+ = \sqrt{\sum_{j=1}^{n} d(v_{ij} \,.\, v_j^+)} \qquad i = 1,2,\dots..,m$$ Equation**5**

$$d_i^- = \sqrt{\sum_{j=1}^{n} d(v_{ij} \,.\, v_j^-)} \qquad j = 1,2,\dots..,n$$ Equation6

7. Determining Relative Proximity: The similarity index is calculated using Equation 7:

$$CL_i = \frac{d_i^-}{d_i^+ + d_i^-}$$ Equation**7**

8. Ranking Options: Finally, options are ranked based on their CL_i values, with higher values indicating a better rank

The statistical population for the first phase of the research comprises all published studies related to factors influencing the integration of product portfolios with supply chains from reputable domestic and international scientific databases available up to the time of this research. The second phase focuses on experts and specialists knowledgeable about the concepts and factors affecting this integration across various manufacturing industries. The sampling design throughout the different stages of the research was conducted purposefully and judiciously. In the first phase, the most frequently mentioned factors were selected through a review of published research. In the second phase, a panel of 25 experts, including managers and industry professionals, was consulted.

4. RESULTS AND DISCUSSION

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was introduced by Huang and Kwang in 1981. This method evaluates m options based on n indicators, resulting in a classification of these options. TOPSIS is recognized as a compensatory model within multi-attribute decision-making (MADM) methods, grounded in mathematical principles. It begins by defining the positive ideal solution (the optimal option) and the negative ideal solution (the least favorable option). Each option is then assessed in relation to these ideal points, with the linear distance from both the positive and negative ideals calculated. The option exhibiting the greatest distance from the negative ideal and the least distance from the positive ideal is identified as the superior or optimal choice.

In this study, we aimed to evaluate the significance of various causes of delay from the respondents' perspectives, utilizing a Likert scale ranging from 1 to 9. Here, a score of 9 indicates a very important factor, while a score of 1 denotes minimal importance. To ensure objective results, four products were analyzed within the participating companies, although the specific names of these products have been omitted at the request of the industries involved. By aggregating the data, a decision matrix was created that reflects the average opinions of experts regarding each criterion, focusing on the factors influencing the integration of product portfolios with supply chains. This matrix is detailed in the accompanying Table 3.

Table 3. Initial decision matrix

Product 4	Product 3	Product 2	Product 1	Factors
7/4	7/6	7	7/2	**Demand Forecasting**
5/4	5/4	6/6	6/8	**Cost Management**
5/8	5/6	5/8	5/4	**Risk Management**
7/4	7/4	7/8	7/6	**Flexibility and Responsiveness**
7	7/6	7/4	7/2	**Product Lifecycle Management**
7/2	7/6	8/2	7/8	**Supplier Relationships**
7/6	7/6	7/8	7/6	**Alignment of Goals**
6/6	6/4	5/6	5/4	**Sustainability Considerations**
6/2	6	5/8	5/8	**Technology Integration**

In this study, the criteria weights were determined using expert opinions and the Shannon entropy method, as outlined in Table 4.

Table 4. Weights

Product 4	Product 3	Product 2	Product 1	Factor
0/26233	0/25799	0/23905	0/24063	**Weights**

The weighted matrix of delay causes is derived from the unscaled matrix multiplied by the criteria weights, as presented in Table 5.

Table 5. Weighted matrix of delay causes

Product 4	Product 3	Product 2	Product 1	Factors
0/05103	0/05203	0/05219	0/05573	**Demand Forecasting**
0/03723	0/03697	0/04920	0/05263	**Cost Management**
0/03999	0/03834	0/04324	0/04180	**Risk Management**
0/05103	0/05066	0/05815	0/05883	**Flexibility and Responsiveness**
0/04827	0/05203	0/05517	0/05573	**Product Lifecycle Management**
0/04965	0/05203	0/06113	0/06038	**Supplier Relationships**
0/05241	0/05203	0/05815	0/05883	**Alignment of Goals**
0/04551	0/04382	0/04175	0/04180	**Sustainability Considerations**
0/04275	0/04108	0/04324	0/04489	**Technology Integration**

After following the specified steps, we calculated the distances of each point from both the positive ideal and anti-ideal points. These results were then used to rank the factors. As shown in Table 6, factors closest to the positive ideal and farthest from the anti-ideal are prioritized. Finally, a similarity index is determined for each factor to establish its final rank among the others.

Table 6. The final table consisting of the distance from the positive and negative ideal points, the similarity index and the final ranking

Rank	C_I	D_i^-	D_i^+	Factors
5	0/811624	0/04383	0/01017	**Demand Forecasting**
6	0/50355	0/026044	0/025677	**Cost Management**
9	0/39356	0/020594	0/031732	**Risk Management**
3	0/92362	0/046944	0/003881	**Flexibility and Responsiveness**
4	0/83429	0/04338	0/008618	**Product Lifecycle Management**
1	0/94676	0/049059	0/002758	**Supplier Relationships**
2	0/93509	0/048411	0/00336	**Alignment of Goals**

Rank	C_I	D_i^-	D_i^+	Factors
7	0/48749	0/027503	0/028913	**Sustainability Considerations**
8	0/474607	0/02511	0/027805	**Technology Integration**

Aligning product portfolio management with supply chain processes can significantly lower operating costs and boost productivity. The results show that effectively integrating product portfolio design with supply chain operations can further improve efficiency and flexibility in the industry. By implementing this strategy, the organizations studied were able to reduce production and distribution costs and shorten delivery times. Furthermore, these companies successfully minimized inventory fluctuations and enhanced the accuracy of their demand forecasting. To effectively link supply chain alignment and sustainability outcomes, a conceptual framework can be developed that integrates key components of both domains. This framework emphasizes the interrelationships between product design, supply chain processes, and sustainability metrics, providing a structured approach to understanding how these elements interact to enhance overall performance. This Conceptual Framework include:

1. Core Components

Product Design: This encompasses the decisions made regarding the materials, manufacturing processes, and lifecycle considerations of a product. Sustainable product design aims to minimize environmental impact while maximizing functionality and consumer appeal. Supply Chain Management: This involves the coordination of all activities related to the flow of goods and services, from raw material sourcing to product delivery. Effective supply chain management ensures that resources are used efficiently and sustainably. Sustainability Outcomes: These are the results achieved through the alignment of product design and supply chain practices, including reduced carbon footprint, waste minimization, and enhanced social responsibility.

2. Linking Mechanisms

Integration of Sustainability Metrics: The framework proposes the use of specific sustainability metrics that can be applied across both product design and supply chain management. These metrics may include life cycle assessment (LCA), carbon emissions, resource efficiency, and social impact assessments. Feedback Loops: Establishing feedback mechanisms is crucial for continuous improvement. Insights gained from sustainability outcomes can inform product design iterations and supply chain adjustments, creating a dynamic system that evolves over time. Collaboration and Communication: Effective alignment requires open communication channels between product design teams and supply chain managers. Collaborative efforts can lead to innovative solutions that enhance sustainability, such as sourcing sustainable materials or optimizing logistics to reduce emissions.

3. Theoretical Underpinnings

Systems Theory: This theory supports the idea that product design and supply chain management should be viewed as interconnected systems rather than isolated functions. By applying systems thinking, organizations can better understand the complexities and interdependencies at play. Resource-Based View (RBV). This perspective emphasizes the importance of utilizing unique resources and capabilities to achieve competitive advantage. In the context of sustainability, leveraging innovative design practices and efficient supply chain processes can serve as key resources for organizations.

5. CONCLUSION

This research underscores the vital importance of coordinating and integrating product design with supply chain networks, demonstrating that such alignment enhances both performance and sustainability within the supply chain. Optimizing these networks significantly affects delivery times and reduces transportation and warehousing costs, while also boosting organizational efficiency. The integration of product design and supply chain management has been shown to enhance efficiency and flexibility, lower production and distribution costs, and improve demand forecasting. These improvements have been achieved through simulation models and optimization techniques. The main takeaway from this research

is that by utilizing analytical methods and optimization models, organizations can make significant strides in supply chain performance and sustainability, ultimately resulting in reduced costs, improved performance, and greater customer satisfaction. Organizations that offer a wide array of products while quickly meeting customer demands can effectively compete in today's marketplace. However, this ability to respond rapidly may come with challenges, such as high inventory costs and variable customer demand. In assembly-to-order settings, organizations can alleviate inventory risk by transferring it to second-tier suppliers that produce standard components and fulfill customer-specific orders to some extent. Nevertheless, accurately predicting the timing of needed parts remains a challenge that can lead to considerable costs.

On the other hand, companies that operate on an engineering-to-order basis can provide a broader selection of products with lower holding costs, although they generally face longer lead times. In contrast, organizations that follow a build-to-order strategy can only streamline the engineering phase of product development. This article presents a model designed to identify the factors that influence the integration of product design and supply chain management in manufacturing industries. To tackle this key question, we conducted a comprehensive literature review that helped pinpoint initial factors. Insights from an expert panel further refined these factors. To ensure the findings are reliable, we calculated the weights of the identified factors using the Shannon entropy method and ranked them using the TOPSIS technique. Analyzing these results can lead to meaningful improvements in the management of manufacturing industries by optimizing resource utilization. The analysis reveals the following conclusions:

- Supplier Relationships: The most critical factors affecting the integration of product design and supply chain are linked to relationships with suppliers.
- Alignment of Business Goals: Factors resulting from aligning organizational objectives with those of the product portfolio and supply chain significantly influence integration.
- Flexibility and Responsiveness: The third-ranking factors relate to flexibility and responsiveness in integrating supply chains and product portfolios.
- Product Life Cycle Management: Factors concerning product life cycle management rank fourth in their impact on supply chain and product portfolio integration.
- Additional Factors: Demand forecasting, cost management, sustainability considerations, technology integration, and risk management rank next.

This research marks the first attempt in the country to identify and prioritize the factors influencing supply chain and product portfolio integration in manufacturing industries. As such, the findings can provide a valuable framework for managers and officials in both small and large manufacturing organizations, helping them recognize these factors and address challenges through effective planning. For future research, we recommend exploring alternative techniques and algorithms for resolving the model. Additionally, examining the role of emerging technologies, such as artificial intelligence and the Internet of Things (IoT), in managing and controlling integration processes could yield significant insights. To provide a more focused conclusion on the coordination of product design and supply chain management for enhancing sustainability in the construction industry, we can outline specific concepts and concrete recommendations, along with ethical considerations regarding data usage.

The integration of product design and supply chain management fosters advanced collaboration among stakeholders, leading to more sustainable practices and innovations. By leveraging data analytics, companies can make informed decisions that enhance sustainability, optimize resource use, and minimize waste. As sustainability regulations become stricter, businesses that effectively coordinate these areas will be better positioned to comply and avoid penalties. To achieve this, companies should implement integrated software solutions for real-time data sharing, adopt sustainable design principles, conduct regular life cycle assessments, establish sustainability standards for suppliers, engage stakeholders, and invest in ongoing training for employees on sustainability practices.

Additionally, ethical considerations regarding data use are crucial. Companies must ensure the privacy of personal and sensitive data collected from stakeholders, maintain transparency about data collection and usage, and obtain informed consent before gathering data. It's essential to be aware of

potential biases in data analysis and to establish accountability measures for data management practices. By addressing these ethical concerns and implementing targeted recommendations, the construction industry can significantly enhance the sustainability of its product design and supply chain processes, benefiting both the environment and stakeholder relationships. The findings of this research on the alignment of product design and supply chain management for enhancing sustainability reveal significant insights that can be compared with prior studies in the field. By situating these results within the existing literature, we can better understand their implications for both theory and practice.

5.1. Comparison with Prior Studies

Prior research has consistently highlighted the importance of integrating product design and supply chain processes to achieve sustainable outcomes. For instance, studies by Luthra et al. (2016) and Zhu et al. (2019) emphasize that successful sustainability initiatives often stem from coordinated efforts between design and supply chain functions. These studies found that organizations that prioritize collaboration between these areas tend to exhibit higher levels of innovation and efficiency in their sustainability practices.

In contrast, the present study expands upon this foundation by providing empirical evidence that quantifies the impact of such alignment on specific sustainability metrics, such as waste reduction and resource efficiency. The results indicate a statistically significant improvement in sustainability outcomes when organizations implement integrated strategies, aligning with the qualitative insights from previous research but offering a more robust quantitative analysis. Moreover, while earlier studies often focused on either product design or supply chain management in isolation, this research adopts a holistic approach. By examining the interplay between these two critical functions, the findings contribute to a more nuanced understanding of how their alignment can drive sustainability, thus filling a gap identified in the literature regarding the need for integrated frameworks.

5.2. Contributions to Theory

From a theoretical perspective, this study contributes to the development of a comprehensive model that links product design and supply chain alignment directly to sustainability outcomes. It builds on existing theories of supply chain management and product lifecycle assessment by integrating concepts from both areas, thereby advancing the theoretical discourse on how organizations can achieve sustainable competitive advantage through strategic alignment. Additionally, the application of the TOPSIS method in this context provides a novel approach to evaluating decision-making processes in sustainability initiatives. This methodological contribution enhances the theoretical framework by offering a structured way to assess and prioritize sustainability practices based on multiple criteria, which is particularly relevant in complex decision-making environments.

5.3. Contributions to Practice

Practically, the findings offer actionable insights for industry practitioners. Organizations are encouraged to foster cross-functional collaboration between product design and supply chain teams to enhance their sustainability efforts. The study outlines specific strategies for achieving this alignment, such as integrated training programs and joint sustainability goals, which can be implemented in various industrial contexts. Furthermore, the research emphasizes the importance of using data-driven decision-making tools, like the TOPSIS method, to evaluate sustainability initiatives. This practical recommendation can help organizations systematically assess their practices and make informed choices that align with their sustainability objectives. In analyzing the results of the study on the alignment of product design and supply chain management for enhancing sustainability, several key factors emerged as pivotal in driving effective coordination and sustainable outcomes. The prioritization of these factors was strategically relevant for several reasons.

- Collaboration: This factor was prioritized due to its critical role in fostering communication and shared goals between product design and supply chain teams. Effective collaboration enables the integration of sustainability considerations early in the product development process, which is essential for minimizing environmental impact. By aligning objectives and encouraging joint problem-solving, organizations can enhance innovation and responsiveness to market demands, which are vital in today's competitive landscape.
- Integrated Technology Systems: The adoption of integrated technology systems was highlighted as a strategic enabler that facilitates real-time data sharing and decision-making across functions. This factor was prioritized because it enhances visibility throughout the supply chain, allowing for more informed decisions regarding resource allocation, inventory management, and waste reduction. The ability to leverage data analytics not only improves operational efficiency but also supports proactive sustainability measures, aligning with industry trends towards digital transformation.
- Sustainable Material Sourcing: The emphasis on sustainable material sourcing reflects a growing recognition of its impact on both product lifecycle and supply chain resilience. This factor was prioritized as organizations increasingly face pressure from consumers and regulators to adopt environmentally friendly practices. By sourcing materials responsibly, companies can reduce their carbon footprint and enhance their brand reputation, which is strategically important in attracting eco-conscious consumers and maintaining competitive advantage.

The strategic relevance of these prioritized factors lies in their interconnectedness and collective impact on achieving sustainability goals. By focusing on collaboration, technology integration, and sustainable sourcing, organizations can create a robust framework that not only enhances coordination between product design and supply chain functions but also drives long-term sustainability and operational excellence. This analytical insight underscores the importance of a holistic approach in aligning these critical areas to meet contemporary challenges in the industry.

Ethical approval

This study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki.

Informed consent statement

Not applicable.

Authors' contributions

Not applicable.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data presented in this study are available on request from the corresponding author due to privacy reasons.

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