Design and Prioritization of Development Strategies in Sustainable Materials Engineering through the Regnier's Abacus

Raúl José Martelo Gómez[1], Rafael Julio Madrid García[2], David Antonio Franco Borré[3]

[1]*Tenured Research Professor, Systems Engineering Program, Universidad de Cartagena, Colombia*
[2]*Tenured Professor, Civil Engineering program, Universidad de Cartagena, Colombia*
[3]*Tenured Research Professor, Systems Engineering Program, Universidad de Cartagena. Cartagena, Colombia*
Email: rmartelog1@unicartagena.edu.co

Published: 15 March, 2024

Abstract: Sustainability in manufacturing has positioned itself as a new innovation-oriented priority with the capacity to transform the way of doing business by implementing strategies that minimize environmental impact and promote efficiency in the use of resources. However, its implementation faces significant technical, regulatory, and ethical barriers that must be addressed comprehensively. This research approaches the state of sustainable strategies in manufacturing through an exhaustive review of the scientific and technical literature along with semi-structured interviews with experts in sustainability, manufacturing, regulations, and technology and, in addition, through the use of the Regnier's Abacus.

The results revealed the importance of implementing sustainable regulations and the use of circular production systems, as well as the need to prioritize training/teaching in sustainability and the use of innovative technologies. The study also highlighted the importance of having valuable and practical information to guide responsible industrial decision-making, although it also makes clear that more studies are needed on these topics to develop clearer regulations and ethical positions that serve as a guide in the implementation of development strategies in the field of sustainable materials engineering.

Keywords: industrial sustainability, sustainable regulations, circular manufacturing, optimization technologies, Regnier's Abacus.

1. Introduction

Sustainable materials engineering is a vital field to develop and address the problems of climate change, scarcity of natural resources, and environmental sustainability (Tiwari, 2023). This engineering can be defined as an interdisciplinary field that seeks advanced materials with the potential to meet needs, reduce environmental impact, and encourage the application of circular economy principles such as recyclability, biodegradability, and energy efficiency (Ashby, 2012; Li et al., 2022).

In this sense, the need to develop effective strategies dedicated to optimizing the design, production, and application of these materials goes hand in hand with the Sustainable Development Goals (SDG) promulgated by the United Nations, which prioritize industry, innovation, and infrastructure (SDG 9) and consumption and production under sustainable conditions (SDG 12) (Lee et al., 2016). Different studies have begun to investigate the development of sustainable materials and the transition towards the exploitation of a "greener" economy. Ashby (2012), for example, comments that sustainable design models bring with them a significant reduction of negative impacts in the life cycle of materials.

On the other hand, Hegab et al. (2023) comment that collaborative strategies between industry sectors are essential to optimize the use of resources in terms of the carbon footprint. However, although reverse engineering models or life cycle analysis have been initiated for the sustainable vision of materials, this reflects the existence of a gap in the definition of development strategies (Chang et al., 2014), especially in the area of applications that are suitable for specific contexts, well applied and supported by complete qualitative evaluations (Bocken et al., 2016).

Despite the progress made in the field of sustainable materials research, the implementation of practical strategies that take into account technical feasibility and social and economic demands remains a challenge (Tang & Zhou, 2012). Malek and Desai (2021) warned that the absence of participatory methodologies to select and prioritize strategies limited the impact of scientific advances on the industry. Likewise, decisions linked to the development of these materials are often disconnected, and generally, a fragmented development of advanced materials is carried out without a global vision taking into account the views of experts in the sector (Diaz et al., 2021).

The present study aims to fill these gaps by applying the Regnier's abacus technique since this is a participatory resource through which strategies can be collected, analyzed, and prioritized under consensus (Camarena et al., 2022). The choice of this methodology was motivated by its effectiveness in decision-making in complex contexts and in a way that allows the participation of experts in the field.

This research is relevant in contributing to the development of sustainable materials and its development also has important implications for sectors of great interest to the economy in transition towards low-carbon economies; in particular, the construction sector, energy, and the transportation sector (Wang et al., 2018). The aim of the research is to develop and prioritize development strategies for sustainable materials engineering by integrating a documented review and the Regnier's abacus technique, which allows for identifying innovative solutions, evaluating them in a participatory manner, and establishing priorities based on technical, environmental, and economic relevance.

This research provides an updated conceptual framework on development strategies in the field of sustainable materials engineering, based on a comprehensive literature review and the application of the Regnier's Abacus technique; it also provides a participatory and reproducible methodology for the prioritization of strategies that can be applied in different industrial and academic contexts; and it offers specific recommendations for the implementation of prioritized strategies so that key actors optimize resources and maximize positive environmental impact.

2. Methodology

This study was descriptive and exploratory with a qualitative methodological design. It is exploratory because it focuses on acquiring the initial knowledge to generate ideas about innovative strategies in sustainable materials engineering, a field that, although emerging, lacks consolidated theoretical frameworks (Hernández et al., 2014); it is also descriptive because it focuses precisely on describing and characterizing the strategy based on interviews and documentary review (Creswell & Poth, 2016). The qualitative design is relevant since it allows for capturing the complexity of the phenomenon in its study and the views of experts, thus delving into the contextual dynamics of the proposed strategies (Weber, 2017).

The sample consisted of 10 experts in sustainable materials engineering. These experts were selected using a purposeful or convenience sampling technique, due to the specificity of the knowledge required (Etikan et al., 2016). This technique was chosen because the participants have professional and academic experience in the relevant area, which can guarantee that the opinions and data collected are of sufficient quality and relevance. In this sense and according to Morse (2000), a sample of 10 experts in qualitative studies is sufficient to obtain theoretical saturation and have a diversity of visions.

The development of the study has followed two main stages: firstly, the systematic search in academic databases such as Scopus, Web of Science, and Google Scholar. Keywords such as “engineering of sustainable materials”, “development strategies”, “Regnier's Abacus”, and “strategies prioritization” have been chosen. The documentary review has been carried out with the aim of contextualizing the phenomenon and providing the theoretical framework to design the interview guide (Okoli & Schabram, 2015).

The Regnier's Abacus technique was then used to consider development strategies; this technique allows for the gathering of structured information since experts judge and weigh the development strategies already proposed. The interviews conducted were semi-structured and guided by a previously designed questionnaire that was subjected to validation through pilot testing with three participants outside the final sample. An adapted version of the Regnier's Abacus, which includes customized rating scales (Table 1), was used to assess development strategies in materials engineering.

Table 1. Regnier’s Abacus Scale

Dark green	5	Very high priority
Light green	4	High priority
Yellow	3	Moderate priority
Fuchsia	2	Low priority
Red	1	Very low priority
White	0	No response

Source: authors

Each statement was assigned a numerical scale corresponding to a range of basic colors (green, yellow, and red), supplemented with lighter shades of green and red to reflect nuances in the opinions expressed as shown in Table 1. The color white was used to represent the blank vote, as established in the Regnier's Abacus methodology.

On the other hand, among the main methodological limitations are those imposed by the sample size, which, although the number of participants is considered a sufficient size in qualitative studies, a small sample size can limit the generalization capacity of the results (Etikan et al., 2016). Despite that, this aspect is justified since the intention of this research is to go beyond finding statistically representative results that only seek generalization from a sample.

Similarly, limitations also occur in the subjectivity of the analysis, since, by using a qualitative approach, the results can be influenced by the interpretation of experts and researchers. To counteract this drawback, triangulation between documented information and interviews was used (Denzin, 2017). At the same time, there is also the dependence on the Regnier's abacus technique; this technique depends both on the assessment criteria being clearly established and on the experts actively participating. In order to minimize this drawback, a strict protocol was drawn up in such a way as to ensure its understanding and applicability.

3. Results

The documentary review allowed for identifying the design of a set of key strategies related to sustainable development in materials engineering. These strategies were grouped into three main categories and can be seen in Table 2.

Sustainable materials design: Use of secondary materials or industrial waste as inputs (Allwood et al., 2013), Development biodegradable and recyclable materials (Ashby, 2012); and Optimization of the design to minimize carbon footprint across the life cycle (Pal et al., 2017).
Efficient production processes: Incorporation of low-energy consumption technologies, such as sustainable 3D printing (Javaid et al., 2021), Use of renewable energy sources in the manufacturing of materials (Eichhorn & Gandini, 2010), and Reduction of waste during production processes through lean manufacturing methodologies (De la Vega-Rodríguez et al., 2018).
Implementation strategies and policies: Creation of circular supply chains to maximize the reuse of materials (Bocken et al., 2016), Promotion of regulations that incentivize the use of sustainable materials in the industry (Tsai & Chou, 2004), and Education and training in sustainable practices for engineers and designers (Ashby, 2012)

Table 2. Strategies for the development of sustainable materials engineering identified in the documentary review

Code	Name of the Strategy	Description of the Strategy
E1	Use of recyclable materials	Incorporation of secondary or recycled materials from industrial waste to reduce environmental impact.
E2	Development of biodegradable materials	Design of materials that decompose naturally without generating toxic waste, promoting their integration into circular economy systems.
E3	Optimization of design to minimize carbon footprint	Use of sustainable design tools to reduce carbon emissions throughout the material life cycle.
E4	Incorporation of low energy consumption technologies	Adoption of advanced manufacturing processes, such as sustainable 3D printing, which require less energy compared to traditional techniques.
E5	Use of renewable sources in manufacturing	Substitution of fossil energy sources with renewable alternatives, such as solar or wind energy, in materials production processes.
E6	Implementation of lean manufacturing to reduce waste	Application of continuous improvement methodologies to minimize waste of resources during production, improving overall efficiency.
E7	Creation of circular supply chains	Design of integrated systems to maximize the reuse of materials and products at different stages of the life cycle.
E8	Promotion of sustainable regulations	Development of policies and regulations that encourage the adoption of sustainable materials in the industry.
E9	Education and training in sustainability	Educational initiatives targeting engineers and designers to encourage greater adoption of sustainability principles in the design and use of materials.

Source: authors, based on bibliographic review.

Based on the above results, a questionnaire was designed to apply the Regnier's Abacus technique and collect the opinions and perceptions of sustainable materials engineering experts on the strategies. The statements related to the strategies were assessed by a weighting based on the degree of agreement or disagreement of the experts, each statement was assigned a numerical scale that corresponded to a range of colors as shown in Table 1. The results obtained are presented below:
The questionnaire responses were arranged in a matrix, where the study statements were presented in rows and the experts in columns, resulting in Table 3. This table presents a visual representation in the form of a mosaic that offers a clear perspective of the qualitative information. This representation makes it easy to visualize the position of each expert regarding the statements on development strategies in sustainable materials engineering.

Table 3. Expert responses presented in the form of a color table

	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
01 How relevant is the use of recyclable materials?										
02 How relevant is the development of biodegradable materials?										
03 How relevant is the optimization of design to minimize the carbon footprint?										
04 How relevant is the incorporation of low energy consumption technologies?										
05 How relevant is the use of renewable sources in manufacturing?										
06 How relevant is the implementation of lean manufacturing to reduce waste?										
07 How relevant is the creation of circular supply chains?										
08 How relevant is the promotion of sustainable regulations?										
09 How relevant is education and training in sustainability?										

Source: authors

In order to determine the areas of agreement and disagreement among the experts, the statements related to the identified strategies were organized progressively from left to right. This order began with the statements that showed the greatest consensus regarding their relevance in the field of sustainability and moved toward those with the greatest discrepancies. In the middle were the statements that reflected a balance between consensus and disagreement, or a preponderance of divided opinions. Table 4 presents the color palette resulting from the analysis, which visually demonstrates the degree of consensus and divergences observed in the study.

Table 4. Statements ordered by consensus and discrepancies according to the assignment in Table 1

09 How relevant is education and training in sustainability?										
05 How relevant is the use of renewable sources in manufacturing?										
08 How relevant is the promotion of sustainable regulations?										
06 How relevant is the implementation of lean manufacturing to reduce waste?										
03 How relevant is the optimization of design to minimize the carbon footprint?										
07 How relevant is the creation of circular supply chains?										
04 How relevant is the incorporation of low energy consumption technologies?										
01 How relevant is the use of recyclable materials?										
02 How relevant is the development of biodegradable materials?										

Source: authors

As can be seen in the table, experts agreed on prioritizing technical and political strategies that have a direct impact on the reduction of emissions and the use of recyclable resources. The use of secondary materials was highlighted as a temporary and low-cost alternative to mitigate the ecological footprint, in addition to the role of regulations as drivers for companies to adopt sustainable practices.

4. Discussions

The results are in line with the current trend and focus on sustainability in materials engineering (in line with what is described by the scientific literature and the timelines in policies and technologies related to sustainable development).

When comparing the results of the documentary review and the priorities of the experts, there is a good coincidence. The priority given to the development of recyclable materials and the optimization of processes corresponds with previous studies (Ashby, 2012). Regulations, on the other hand, were given more prominence by the experts, since it is a dimension that has been little discussed in the literature reviewed and which is identified in the study as a key pillar for carrying out these actions.

On the other hand, the lower score given to waste reduction through lean manufacturing can be interpreted as lower short-term effectiveness compared to other more immediate measures such as the use of recyclable materials. This result coincides with studies that suggest that the benefits of lean manufacturing are visible when progress has been made in sustainable development (Bocken et al., 2016).

It is natural that the education and training in sustainability pillar receives the highest score since training and education are the tools that enable professionals and users to be trained in sustainable practices. The literature also suggests that education contributes to the adoption of green technologies and initiates the transition towards more responsible practices (Sterling & Orr, 2001). Without this training pillar, the rest of the strategies would lack the knowledge and/or acceptance to be consolidated.

Furthermore, the use of renewable energy in industrial processes has a clear impact on the reduction of emissions and, therefore, on the sustainability of production systems. Many studies argue that the addition of renewable sources will not only act as a means of reducing environmental impact but will also put energy independence into operation (Jacobson & Delucchi, 2011).

On the other hand, sustainable regulations guarantee that industries have a regulatory framework that forces and orders industries to have responsible practices. These laws are very important to standardize efforts in such a way that overall success is guaranteed (Köhler et al., 2019). In addition, the implementation of these laws promotes R&D in the field.

The lean manufacturing implementation strategy to reduce waste is also of high importance, as it focuses directly on the efficiency of industrial processes. The lean manufacturing methodology is widely tested to offer waste reduction (Womack & Jones, 1997) and resource optimization, which is therefore consistent with industrial sustainability objectives.

Similarly, prioritizing design optimization to reduce the carbon footprint is valid, because design has a great effect on shaping the impact of a product throughout its life cycle. Tools such as life cycle analysis allow for optimizing processes and materials to reduce the carbon footprint (Finnveden et al., 2009).

Similarly, circular supply chains allow for avoiding the extraction of natural resources in favor of reuse, thus resulting in recycling. Their incorporation supports the circular economy, which is a current concept, or at least one that is on the rise, in global sustainability strategies (Ghisellini et al., 2016).

Similarly, the inclusion of low-energy technologies could be considered a lower category compared to the previous ones, since the incorporation of this type of technology depends on investment in education as well as the development of regulations. However, its effect is indisputable in relation to the efficiency of energy use and cost reduction (Geels et al., 2016).

Regarding the use of recyclable materials, although it is one of the strong points of the circular economy, it is perhaps better framed if the context is to prioritize waste reduction instead of reuse since its effectiveness will depend on (advanced) recycling technology, its availability, and the use of appropriate infrastructure (Stahel, 2016).
Finally, the development of biodegradable materials can be important, but it can also be in a lower priority position compared to more systemic strategies such as regulations and education. This is because its implementation requires scientific and technical advances that are often in the early stages (Rujnić-Sokele & Pilipović, 2017).

5. Conclusion

This study has reviewed the development strategies in sustainable materials engineering based on a literature review, interviews with experts, and the Regnier Abacus technique. The prioritization of the analysis provided a logical hierarchy in which the first ones are those that lay the necessary foundations to implement the others. Education, regulations, and the use of renewable sources are basic pillars followed by specific actions such as process optimization and materials development.
This prioritization also allows for observing that it is necessary to combine technological concepts, such as the design of sustainable materials, with regulatory and educational strategies. The prioritization of experts shows that sustainable solutions have to be understood in a systemic sense, involving both technical development and the regulatory and educational framework to maximize their impact. It is necessary to adequately recognize concerns related to the promotion of sustainable regulations, the implementation of circular supply chains, and equity in access to sustainable resources. The relationship between industry, researchers, and regulatory authorities is a measure of the development of the respective frameworks that promote the responsible and effective application of sustainable strategies in manufacturing systems.

References

1. Allwood, J., Ashby, M., Gutowski, T., & Worrell, E. (2013). Material efficiency: providing material services with less material production. . Philosophical transactions of the royal society a: mathematical, physical and engineering sciences, 371(1986), 20120496.
2. Ashby, M. (2012). Materials and the environment: eco-informed material choice. Elsevier.
3. Bocken, N., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. . Journal of industrial and production engineering, 33(5), 308-320.
4. Camarena, J., Osorio, F., Rojas, H., Borda, E., Esteban, J., & Tabares-Valencia, J. (2022). Future public policy guidelines for the sustainable development of Guaviare, Colombia for the year 2035. . foresight, 24(2), 248-275.
5. Chang, D., Lee, C., & Chen, C. (2014). Review of life cycle assessment towards sustainable product development. . Journal of cleaner production, 83, 48-60.
6. Creswell, J., & Poth, C. (2016). Qualitative inquiry and research design: Choosing among five approaches. Sage publications.
7. De la Vega-Rodríguez, M., Baez-Lopez, Y., Flores, D., Tlapa, D., & Alvarado-Iniesta, A. (2018). Lean manufacturing: a strategy for waste reduction. New Perspectives on Applied Industrial Tools and Techniques, 153-174.
8. Denzin, N. (2017). The research act: A theoretical introduction to sociological methods. Routledge.

9. Diaz, A., Schöggl, J., Reyes, T., & Baumgartner, R. (2021). Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management. Sustainable Production and Consumption, 26, 1031-1045.
10. Eichhorn, S., & Gandini, A. (2010). Materials from renewable resources. . Mrs Bulletin, 35(3), 187-193.
11. Etikan, I., Musa, S., & Alkassim, R. (2016). Comparison of convenience sampling and purposive samplin. American journal of theoretical and applied statistics, 5(1), 1-4.
12. Finnveden, G., Hauschild, M., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., & Suh, S. (2009). Recent developments in life cycle assessment. . Journal of environmental management, 91(1), 1-21.
13. Geels, F., Berkhout, F., & Van Vuuren, D. (2016). Bridging analytical approaches for low-carbon transitions. Nature climate change, 6(6), 576-583.
14. Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. . Journal of Cleaner production, 114, 11-32.
15. Hegab, H., Shaban, I., Jamil, M., & Khanna, N. (2023). Toward sustainable future: Strategies, indicators, and challenges for implementing sustainable production systems. . Sustainable Materials and Technologies, 36, e00617.
16. Hernández, R., Fernández, C., & Baptista, M. (2014). Metodología de la investigación. México: McGraw Hill.
17. Jacobson, M., & Delucchi, M. (2011). Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. Energy policy, 39(3), 1154-1169.
18. Javaid, M., Haleem, A., Singh, R., Suman, R., & Rab, S. (2021). Role of additive manufacturing applications towards environmental sustainability. Advanced Industrial and Engineering Polymer Research, 4(4), , 312-322.
19. Köhler, J., Geels, F., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., & Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. Environmental innovation and societal transitions, 31, 1-32.
20. Lee, B., Kjaerulf, F., Turner, S., Cohen, L., Donnelly, P., Muggah, R., & Gilligan, J. (2016). Transforming our world: implementing the 2030 agenda through sustainable development goal indicators. . Journal of public health policy, 37, 13-31.
21. Li, J., Song, G., Cai, M., Bian, J., & Mohammed, B. (2022). Green environment and circular economy: A state-of-the-art analysis. Sustainable Energy Technologies and Assessments, 52, 102106.
22. Malek, J., & Desai, T. (2021). A framework for prioritizing the solutions to overcome sustainable manufacturing barriers. Cleaner Logistics and Supply Chain, 1, 100004.
23. Morse, J. (2000). Determining sample size. Qualitative health research, 10(1), 3-5.
24. Okoli, C., & Schabram, K. (2015). A guide to conducting a systematic literature review of information systems research. Sprouts, 10-26.
25. Pal, S., Takano, A., Alanne, K., & Siren, K. (2017). A life cycle approach to optimizing carbon footprint and costs of a residential building. . Building and Environment, 123, 146-162.
26. Rujnić-Sokele, M., & Pilipović, A. (2017). Challenges and opportunities of biodegradable plastics: A mini review. Waste Management & Research, 35(2), 132-140.
27. Stahel, W. (2016). The circular economy. . Nature, 531(7595), 435-438.
28. Sterling, S., & Orr, D. (2001). Sustainable education: Re-visioning learning and change (Vol. 6). Green Books for the Schumacher Society.
29. Tang, C., & Zhou, S. (2012). Research advances in environmentally and socially sustainable operations. European Journal of Operational Research, 223(3), 585-594.

30. Tiwari, A. (2023). Advancement of materials to sustainable & green world. . Advanced Materials Letters, 14(3), 2303-1724.
31. Tsai, W., & Chou, Y. (2004). Government policies for encouraging industrial waste reuse and pollution prevention in Taiwan. Journal of Cleaner Production, 12(7), 725-736.
32. Wang, C., Engels, A., & Wang, Z. (2018). Overview of research on China's transition to low-carbon development: The role of cities, technologies, industries and the energy system. Renewable and Sustainable Energy Reviews, 81, 1350-1364.
33. Weber, M. (2017). Methodology of social sciences. Routledge.
34. Womack, J., & Jones, D. (1997). Lean thinking—banish waste and create wealth in your corporation. . Journal of the operational research society, 48(11), 1148-1148.