

SUSTAINABLE DEVELOPMENT OF METALLURGICAL PRODUCTS BY THE MODELING OF MATERIAL SELECTION THROUGHOUT LIFE-CYCLE

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Abstract

Companies whose business is based on offering new product solutions are seeking techniques that support decision-making at early stages, such as conceptualization and prototyping. The growing importance of sustainable product development necessitates a holistic approach to this process. This is particularly challenging in the metals industry, which primarily focuses on materials, their sourcing, and extraction. These materials are closely linked to the level of satisfaction with the final product. Therefore, they should be considered across the entire product lifecycle. However, there is a lack of techniques to facilitate these decisions in the metals industry. Therefore, the aim of this article is to develop a model that supports the sustainable development of metal products by modeling materials selection throughout the lifecycle. The modeling takes into account key aspects such as quality, environmental impact, social responsibility, costs, and innovation. The model was developed in five main stages, and its main innovation is to consider alternative material solutions within the context of the final product lifecycle.

Keywords: Metallurgy, life cycle assessment, quality, sustainable product development, production engineering

1. INTRODUCTION

The growing demand for lightweight materials and structures with broad applications, as well as growing customer requirements, are making these issues increasingly popular in mechanical, aerospace, and construction engineering [1]. This interest is growing as a result of the pursuit of sustainable development, which is challenging within industrial operations. Modern industries, in particular, whose activities focus on design and development, depend significantly on the availability of key materials. One such activity is the search for and development of diversified production processes that will secure essential elements for the future [2]. Considering materials throughout their entire life cycle is also crucial [3-5].

The authors of [6] aimed to develop a method that takes into account environmental considerations in the selection of alternative materials used in components, so that they meet performance and functionality requirements while simultaneously limiting negative environmental impacts throughout the life cycle. This approach was implemented in the metallurgical process, but also in, for example, refining and life cycle assessment. As in [1], a review was conducted on perforated metal materials (PMM), which are used as construction, finishing, and decorative materials. Sustainability aspects of these materials were considered, such as recycling methods, various properties, and applications, including potential technological waste. The authors of [7] analyzed a simulation model of the development of economic sectors where the metallurgical

industry is the subject of research, including mechanical engineering and the production of finished metal products. Techniques used in the analysis include systems analysis, mathematical modeling of macroeconomic systems, and economic indicators. Another example is the work [8], which analyzed the potential of nonferrous metals residual material flows from metallurgy, including their possible contribution to the security of metals supply in the context of new secondary resources, assuming economic and technical viability. In turn, the paper [2], discussed the potential recovery of selected critical elements from the sulfide ore supply chain, including an assessment of the feasibility of their recovery from waste. Hydrometallurgical practices, including separation, leaching, and ion exchange techniques, were addressed. Furthermore, as in [9], a framework of eco-efficiency indicators was developed that can be used to assess, benchmark, and communicate the sustainability of the copper production value chain.

Modern metallurgy requires the integration of interdisciplinary diagnostic and optimization methods to precisely model the life cycle of materials. The use of computed tomography (CT) enables detailed analysis of internal structure, which directly translates into reliable predictions of long-term product reliability [10, 11]. Simultaneously, optimization of manufacturing processes – particularly in the demanding automotive sector – can be achieved through response surface methodology (RSM). This allows for effective balancing of strength parameters with stringent environmental standards [12]. A key aspect of sustainable development is also the resistance of materials to specific degradation factors. Experience from the biotechnology sector indicates the need to design alloys resistant to biocorrosion and aggressive chemical media, which is a prerequisite for extending the life cycle of components in modern bioindustry [13]. A holistic approach to these aspects in a single decision-making system is the foundation for true sustainability in the metals industry.

The topic of sustainable development of metallurgical products is currently a hot topic. Various supporting solutions are being sought. However, there is a lack of work in this field that addresses life-cycle modeling of materials selection. Therefore, the aim of this research is to develop a model that supports the sustainable development of metallurgical products through a life-cycle modeling approach. The following sections of the article cover the general model concept, assumptions, and framework.

2. CONCEPT AND ASSUMPTIONS

Given the importance of detailed consideration of various materials in the early stages of product development (conceptualization and prototyping), it was deemed appropriate to focus research on the materials acquisition and extraction phase. The research concept encompasses proposing various alternative materials or developing their modifications, followed by assessing their potential usefulness in the final product. The novelty of this research lies in translating these analyses into other life cycle stages, such as production and end-of-life. Therefore, the modeling approach encompasses a "cradle-to-grave" approach. It was assumed that the offered material solutions can be analyzed in terms of quality, environment, society, cost, and innovation. These aspects are to be reflected in the final product. Hence, quality is understood as meeting customer expectations regarding product usability. Environment as negative environmental impact from a product life cycle perspective. Social aspect refers to the social impact or social responsibility associated with the product throughout its life cycle. Cost is the cost of producing and/or purchasing the product. Innovativeness, on the other hand, refers to identifying innovative product solutions compared to existing ones. These aspects are considered only in the context of product materials, the first stage of the life cycle. This is because this stage generates the efficiency of the remaining activities in the life cycle. The general modeling concept is presented in **Figure 1**.

The main assumptions adopted during the modelling process were:

- Materials may be alternative solutions (materials with the same application, of different types) or may represent new material proposals resulting from their individual development;
- Materials are assessed in terms of selected sustainability aspects, and this assessment concerns the compliance with these aspects at individual stages of the final product's life cycle;

- At least three different material proposals are analyzed, but their number should be between 5 and 9 for effective comparison;
- Materials subject to analysis should be selected with the goal of achieving a satisfactory final product.

The assumptions are presented in a systematic way in a synthetic description of the model, as presented in the next part of the study.

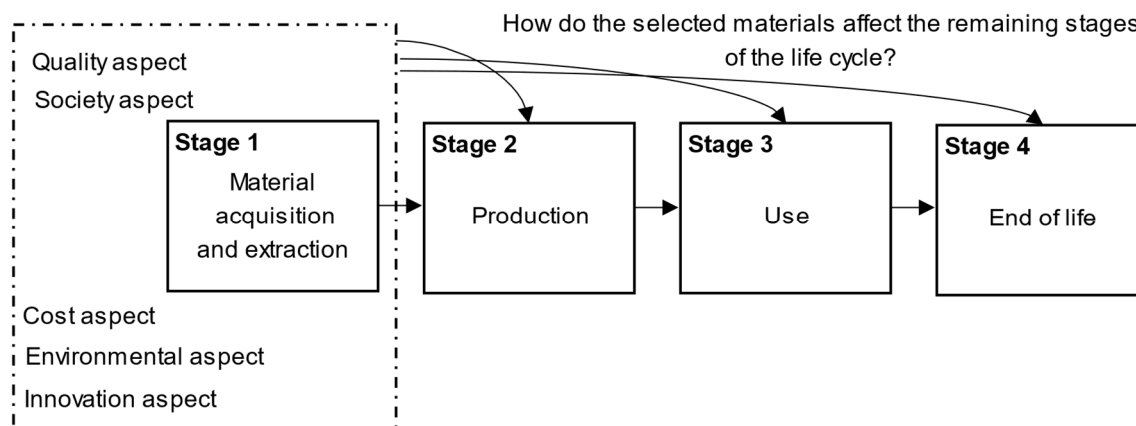


Figure 1 General concept of modeling by material selection

3. RESULTS

Based on the adopted research concept, including specific assumptions, a model for the sustainable development of metallurgical products was developed. It is based on modeling material selection in relation to the final product life cycle. The model is presented in five stages, as shown in **Figure 2**.

The material selection modeling process for sustainable metallurgical product development is described in five main stages. Stage (1) product selection for analysis involves identifying the product requiring improvement actions. Decisions in this regard are made by the entity using the model, e.g., a company manager, designer, or production engineer. Individual preferences, as well as factors such as the product's life cycle (maturity phase), customer requirements, and market dynamics, should be considered during the selection process. Stage (2) identifying product criteria for improvement involves determining which criteria can provide a noticeable increase in customer satisfaction across life cycle stages. Criteria, such as weight, height, power, tensile strength, corrosion resistance, density etc., are selected by a team of experts (e.g., designer, technologist, manager, engineers, etc.), based on previous improvement efforts, knowledge, and experience, as well as market research based on competitive products. The number of criteria may vary, but should not be less than 10 for moderately complex products. Stage (3) developing material alternatives or new materials involves proposing at least three different material alternatives for a single criterion. This may be the current material and two alternative materials, e.g., steel, aluminum, copper. It is assumed that no more than 7 ± 2 [14] material alternatives should be proposed (taking into account the base material – the current one). Material analysis should be performed by a team of experts who consider the possibility of their use in the final product in the context of the life cycle. Stage (4) – evaluation of materials in terms of selected aspects – involves assessing materials in terms of quality, environmental impact [15], innovation [16], society and cost [17]. The evaluation is performed by a team of experts, using, for example, a Likert scale or other methods. A key element of the assessment is verifying the impact of materials on individual stages of the life cycle, which means deciding whether a given material will be beneficial in terms of production, use, and end-of-life [18]. These decisions should be considered in terms of the aforementioned aspects. Assigning weights to these aspects may also be important. Aspect weights and material ratings can be processed using any method.

Materials should be assessed separately for each aspect. The assessment results should be within the same range. Otherwise, they should be normalized to a value between 0 and 1.

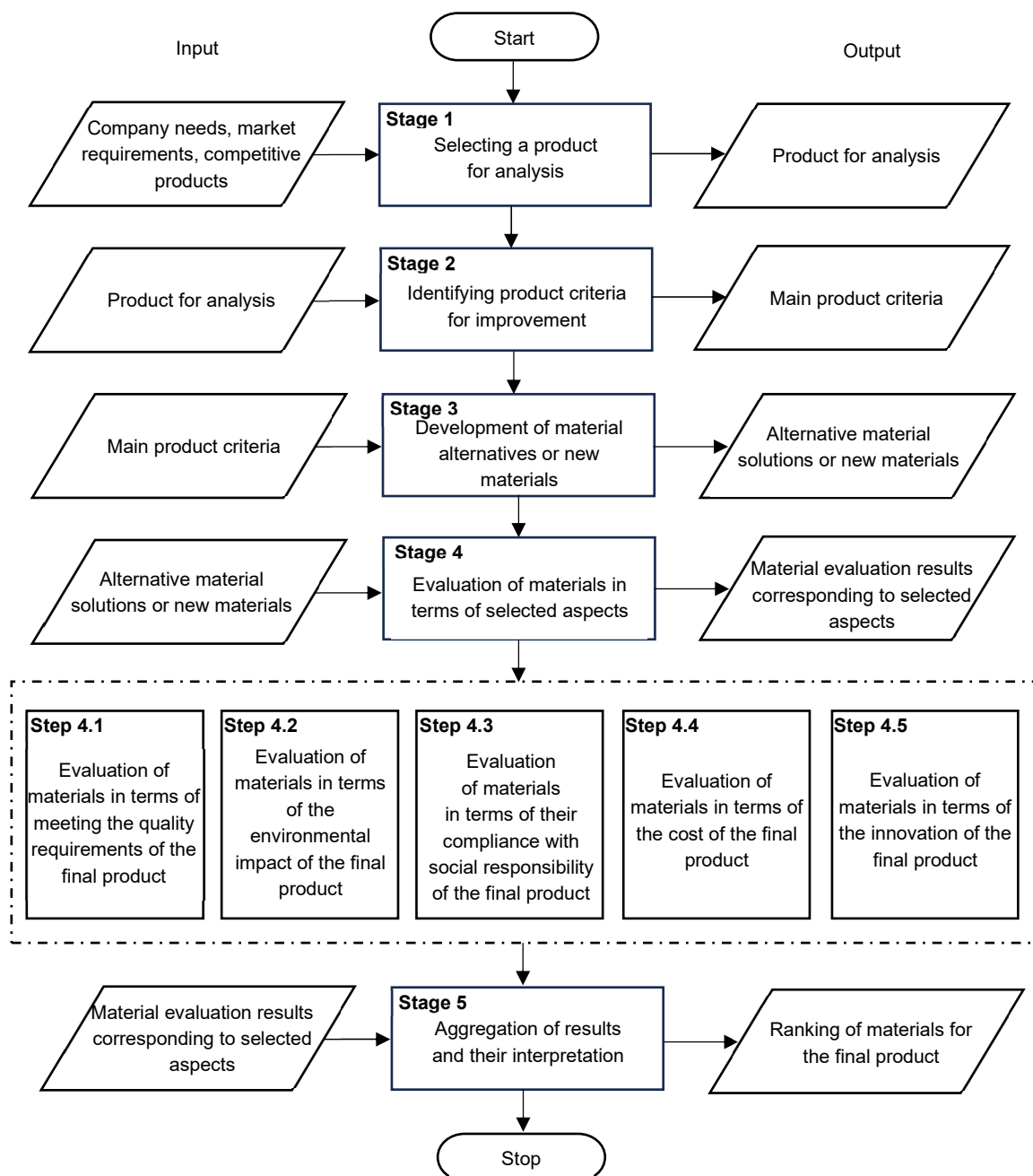


Figure 2 Algorithm for the sustainable development of metallurgical products supported by a material selection model

Step (5) involves aggregation of results and their interpretation. If development decisions are made taking into account all aspects simultaneously (quality, environment, society, cost, and innovation), the proposed model assumes aggregation of decision indicators (obtained in step 4). Aggregation involves calculating the arithmetic mean of the considered decision indicators. According to the proposed concept, the higher the value, the more preferable the material in terms of the sustainability of the metallurgical product. Interpretation of results can be performed according to a scale of relative states. Morphological analysis is also possible. In this

case, only those materials that best meet the simultaneous aspects of quality, environment, social responsibility, innovation, and cost are selected.

4. CONCLUSION

The aim of this article was to develop a model supporting the sustainable development of metallurgical products by modeling materials selection throughout the life cycle. The model operates in five main stages. The model's application is based on the analysis of materials according to key aspects during the selection of materials for final products. These aspects include quality (customer satisfaction), environmental impact throughout the life cycle, social responsibility of the product, purchasing and/or production costs, and product innovation. The model allows for the evaluation of alternative material solutions within the context of the final product's life cycle. The main benefits of the proposed model include:

- Adapting the material selection decision-making process early in product development;
- Focusing the decision-making process on different design solutions, depending on different materials for key product criteria;
- Ensuring the aggregation of quality, environmental, social, cost, and innovation aspects into a single, coherent approach;
- A simple model applicable to initial development decisions in the metals industry.

The model also has certain limitations, such as basing the decision-making process on the knowledge and experience of a team of experts. This can lead to inconsistencies and subjectivity resulting from traditional teamwork. At the same time, the model can be effective when applied to a relatively small number of criteria and offered material alternatives. Another limitation is the lack of computer support, which can lead to time-consuming calculations and potential errors. Therefore, future research will rely on computerizing the model. Various tests of the model for specialized products from the metallurgical industry are also planned.

The model will find application in the metallurgical industry, given its intended use in material needs analysis. However, it may be useful in other industries that undertake product design and production activities, such as the electrical machinery industry.

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