

AGGREGATION OF QUALITY, ENVIRONMENT AND COST: MODEL FOR IMPROVING METALLURGICAL PRODUCTS

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Abstract

The metallurgical industry, which is key to the economy, dynamically combines tradition with modernity, striving for profitability and innovation. In the context of sustainable development, the aim of the article is to develop a six-stage model for improving metallurgical products, taking into account quality, environmental impact and costs. The model is based on the indicator assessment (WSM) of quality and environmental criteria and their importance in relation to current products and prototypes. The results of the quality and environmental analysis are combined with the costs of prototypes. The novelty of the model is the multi-criteria assessment and classification of metallurgical product prototypes in terms of sustainable development, which can support managers in their improvement.

Keywords: Metallurgy, product improvement, sustainable development, Life Cycle Assessment, cost analysis

1. INTRODUCTION

The current product development paradigm in metallurgy encompasses performance, quality, production costs and environmental impact [1-3], with quality often being the top priority [1]. The improvement of metallurgical products is complex due to aspects such as the material metallurgy, mechanical behavior and interactions with other components, as well as the difficulty in precisely defining the product design for quality in the forming process [2]. Cost optimization, in addition to improving quality and considering the environment [2, 5], is a significant challenge for manufacturers in this industry [4, 5].

Strong competition forces the search for new product solutions, especially in metallurgy, where the share of non-standard products is growing [6]. In order to improve quality and reduce costs, Six Sigma [7], material flow simulations [1], bimetallic rolls [2] and continuous casting process optimization [8] were used. Nonconformities of metal products were also analyzed using quality management techniques [9, 10]. Integration of costs with the reduction of the impact on the environment, e.g. SO₂ emissions [5], and the impact of galvanizing conditions on waste and their processing technologies for zinc recovery [11] were also studied.

The improvement of metallurgical products with regard to sustainable development is in the development phase. The aim of the article was to develop a model supporting this improvement by taking into account quality, environmental impact in the life cycle and costs. The model is presented synthetically, describing its concept, assumptions and scheme of operation with characteristics of the main stages.

The presented model for enhancing metallurgical products through the integration of quality, environmental considerations, and costs demonstrates relevance to several key areas of research and industrial

development. The emphasis on minimizing the environmental impact [12,13] of metallurgical processes and products aligns with growing global sustainability efforts. While the paper focuses on a modeling approach, the practical implementation of improved metallurgical products could potentially involve advanced material processing techniques such as forging [14] to enhance their durability and performance. Furthermore, the development of new and improved alloys or surface treatments might draw upon the principles of biomaterials [15,16] science, seeking inspiration from or compatibility with biological systems in specific applications. Techniques like electro-spark deposition [17] or special coatings [18,19] could be explored to enhance the surface properties of metals, improving resistance to wear, corrosion, or other forms of degradation. While not explicitly detailed, the energy efficiency of metallurgical production, a crucial factor in cost and environmental impact, connects to the broader field of energy optimization [20]. Finally, advanced manufacturing processes, including potential applications of laser machining [21,22] for precise shaping or surface modification, could play a role in realizing the improved product designs identified by the model.

2. CONCEPTION AND ASSUMPTIONS OF MODEL

An aggregated model for the evaluation of metallurgical product prototypes in terms of sustainable development (quality, environmental impact LCA, costs) was developed. The results of quality, LCA and cost assessments are aggregated into the QEC index, based on which a ranking of prototypes is created, supporting the selection of the most advantageous production solution (high quality, environmental friendliness, moderate cost). The model is dedicated to physical metallurgical products, known to experts (generalization assumptions based on [5, 9, 11, 23]). The number of criteria (quality, environmental, cost) should be about 7 ± 2 (up to 15 or more for complex products) [24]. Quality is expressed by usability (customer satisfaction), environmental impact by the burden in the life cycle, and cost by the cost of production/purchase. The main assumptions of the model are discussed in the characteristics of its stages.

3. RESULTS: MODEL AND PRESENTATION OF ITS FUNCTIONING

Figure 1 shows the design of a model for improving products from the metallurgical industry. It is presented by dividing it into the main stages of the model.

Stage 1. Selection of quality criteria. The team of experts selects quality criteria (basic features of the product functionality for customers) based on the product catalog, e.g. using brainstorming. These criteria include, e.g., type of material, hardness, thickness, weight, often also mechanical strength, chemical purity, alloy composition and durability. It is assumed that the number of quality criteria is a priority over environmental criteria, selected in the next stage.

Stage 2. Selection of environmental criteria for the product. As before, the expert team selects environmental criteria concerning the impact of the product on the environment throughout its entire life cycle [25], e.g. material acquisition, production, use, end of life ("from cradle to grave" [26]). It is possible to include a general criterion of negative impact or to define criteria for environmental burdens, such as CO₂ emissions, eutrophication, ozone depletion or water pollution (lists of criteria, e.g. in [27]). Decisions on environmental criteria depend on the needs of the analysis.

Step 3. Determining the importance of quality and environmental criteria. Due to the different weight of the quality and environmental criteria, the team of experts assigns them importance ratings (weights) on a scale of 1-5 (1 – least important, 5 – most important) [28]. These weights influence the further assessment of the criteria in the next stage.

Stage 4. Indicator assessment of quality and compliance with environmental impact. This stage concerns the evaluation of the current product in terms of quality (customer satisfaction) and environmental impact (QE indicator). It requires characterizing the product criteria (qualitative and environmental) by their

current status (e.g. value, description from the product catalog). Then the product is evaluated on a scale of 1-5 (1 – does not meet expectations/high negative impact, 5 – fully meets/negligible negative impact). Taking into account the weights of the criteria, an indicator assessment of compliance is carried out using the weighted sum model (WSM) (1) [29]:

$$QE = \sum_{i=1}^n w_i a_i \quad (1)$$

where: w_i – i -th assessment of the importance of the criterion, a_i – i -th assessment of the fulfilment of the criterion.

A higher QE index is more beneficial (higher quality with lower negative impact on the environment). The interpretation of the index can be based on a scale of relative states (e.g. [30]). The result of this stage is an indication of the need for improvement actions, discussed in the next stage of the model.

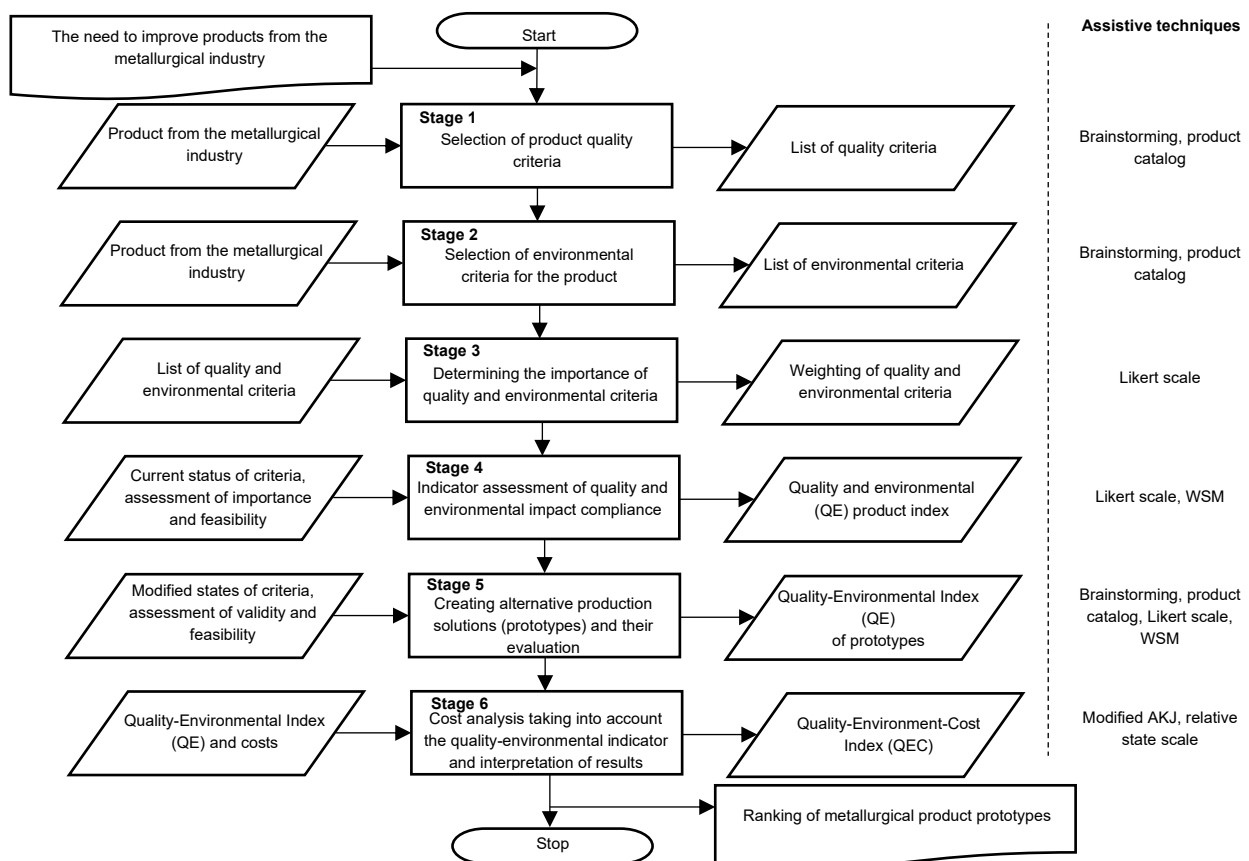


Figure 1 A model for improving products from the metallurgical industry

Stage 5. Creating alternative production solutions (prototypes) and their evaluation. In this crucial stage, the expert team explores new manufacturing solutions, conceptualized as prototypes, by redefining the product's quality and environmental criteria. This process integrates market trend analysis, customer feedback (VoC), and benchmarking, as well as creative techniques such as TRIZ. For metallurgical products, rapid prototyping (e.g., 3D printing for materials testing [31], CNC machining for lightweight components, casting simulations for heavy products) and FEM simulations [32] are crucial for the virtual and physical assessment of mechanical behavior and structural integrity. Prototypes are then indicatively evaluated using a Likert scale

for predicted quality and environmental impact, reflecting step 4, to create a solid foundation for subsequent cost analysis and comprehensive decision-making.

Stage 6. Cost analysis taking into account the quality-environmental indicator and interpretation of results. In the context of sustainable development, production/purchase costs are also important [13]. The expert team estimates these costs for prototypes, interpreting them in terms of their quality and environmental criteria. In order to link costs to the *QE* indicator, a modified cost-quality analysis (CCA) [30] was used, making costs dependent on quality and environmental aspects. The *QE*-dependent cost index (c_k) is calculated, followed by the relative cost (k), the cost-quality-environment proportionality index (E) and the relative cost index (c) (2):

$$c_k = \frac{K}{QE} \quad k = \frac{K_a - K}{K_a - K_i} \quad E = \frac{k}{qe} \quad c = \frac{c_{ka} - c_k}{c_{ka} - c_{ki}} \quad (2)$$

where: K – prototype cost, QE – quality-environmental indicator, K_a – maximum cost among all analyzed costs, K_i – minimum cost among all analyzed costs, k – relative cost, qe – quality-environmental indicator expressed as a decimal fraction, c_{ka} – maximum cost indicator among all analyzed costs, c_{ki} – minimum cost indicator among all analyzed costs, c_k – cost indicator. A higher value of E (especially $E > 1$) indicates a less favorable balance, suggesting higher costs relative to the quality-environmental performance, while E closer to $0 \div 1$ implies a more desirable trade-off.

Next, the decision function index (d) is calculated as in the formula (3):

$$\begin{aligned} \text{when } E = 0 \div 1 & \quad \text{then} \quad d = 0.5 \cdot E \\ \text{when } E > 1 & \quad \text{then} \quad d = 0.5 + 0.5 \cdot (1 - 1/E) \end{aligned} \quad (3)$$

This function transforms the proportionality index E into a normalized decision metric, where higher values of d generally indicate a better overall balance. Then, assuming the assumptions for the resolution rate for the technical (R_t) (4) and economic (R_e) (5), preferences, the average decision resolution rate (R_d) is estimated (6):

$$R_t = \frac{\alpha qe + \beta d + \gamma c + \delta k}{\alpha + \beta + \gamma + \delta} \quad \alpha: \beta: \gamma: \delta = 8: 4: 2: 1 \quad R_t = 0.0667(8qe + 4d + 2c + k) \quad (4)$$

$$R_e = \frac{\alpha k + \beta c + \gamma d + \delta qe}{\alpha + \beta + \gamma + \delta} \quad \alpha: \beta: \gamma: \delta = 8: 4: 2: 1 \quad R_e = 0.0667(8k + 4c + 2d + qe) \quad (5)$$

$$R_d = \frac{R_t + R_e}{2} \quad (6)$$

where: qe – quality-environmental indicator expressed as a decimal fraction, d – decision-making function indicator, c – relative cost indicator, k – relative cost.

Finally, prototypes are classified based on their decision index (R_d or QEC). A higher index signifies a more favorable prototype, indicating a superior combination of high quality, lower environmental impact, and reduced cost. This comprehensive aggregated index directly supports product development decisions, enabling managers to select the most advantageous production solution for sustainable growth.

4. DISCUSSION AND CONCLUSIONS

This article presents a novel, six-step model aimed at improving metallurgical products by integrating quality, environmental impact, and cost. Designed to guide product development and streamline prototyping decisions, the model supports the prediction of alternative production solutions and aims to reduce resource waste. A key advantage of the model is its holistic, multi-criteria assessment, combining technical performance, environmental impact over the product lifecycle, and economic viability within a unified QEC metric. This integrated approach allows for more informed and sustainable prototype selection, going beyond traditional

single-objective improvement methods such as Six Sigma or isolated LCA studies. By systematically evaluating alternative products, the model directly supports sustainability goals in the metallurgical industry, which is crucial given the sector's significant environmental impact. However, the model has limitations. Its reliance on expert input introduces a degree of subjectivity, potentially impacting the consistency and generalizability of results. The use of estimation analyses rather than purely empirical data can also impact accuracy. Furthermore, the current iteration focuses only on direct customer input, going beyond the initial Voice of the Customer analysis, which could be expanded to better align with the market. Future work will focus on validating and generalizing the model through case studies of various metallurgical products in industrial settings. This practical application will help refine its steps, assess its scalability, and explore the integration of advanced analytical tools, potentially including machine learning algorithms, to achieve more robust predictive capabilities and reduce reliance on purely subjective expert judgment.

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