Materials Selection in Product Development: Challenges and Quality Management Tools

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Abstract. Selecting the optimal material from a wide range of competitive variants significantly affects the final technical success of the product development. It avoids undesirable cost consequences and possible premature failure in the marketplace. Today, among the criteria for choosing materials, the emphasis has shifted more towards considering economic aspects and environmental impact. Various defects can occur during the life cycle of a material, from the production of original components to the commissioning of a product in the field. The nature of the deficiencies must be quickly identified and appropriate action taken. It has created a tendency to solve material selection problems using root cause analysis as the most useful problem-solving method in the engineering toolbox. The concepts and step-by-step methodology selected for research quality management tools in root cause analysis (Cause and Effect Analysis, Failure Mode and Effects Analysis, Quality Function Deployment, and Life-cycle Assessment) are considered in the paper. The main advantages and disadvantages of each method are established. Practical cases of using these methods to decide concrete applied problems in polymer materials science are described.

Keywords: Product innovation · Sustainable manufacturing · Root cause analysis · Cause and Effect Analysis · FMEA · QFD method · Life-Cycle Analysis · Life-Cycle Assessment · Process innovation

1 Introduction

At the base of materials science are the well-known paradigm (Fig. 1) about the relationship between the material structure, the processing methods for obtaining this material, and the resulting material properties. A complex combination of all these aspects provides material performance in a specific application [1].

Ultimately, materials affect product function, customer satisfaction, manufacturing systems, product lifecycle, who uses or manufactures it, usability, product identity, work environment, and cost [2].

Selecting an appropriate material or group for product design is often a complicated, responsible, and complex task for engineers. Material selection is a tedious task in

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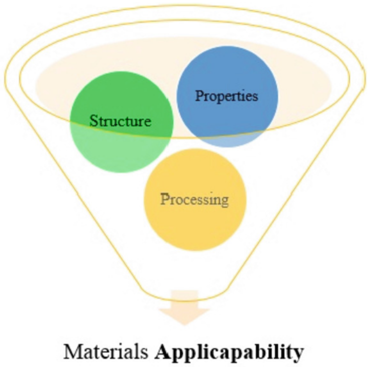


Fig. 1. Materials science paradigm.

manufacturing because many factors need to be carefully assessed before making a final decision [3]. The basic requirements may vary from application to application. Still, several other interrelated factors may also need to be considered depending on the operating environment, making the selection process more complex and time-consuming [4]. In the past, material selection was only a small part of the design process. Therefore, it did not receive the same level of research and development as other areas of design [2].

Nevertheless, few methods have been developed to solve material selection problems, some of which can be applied to material selection and any design selection procedure [5]. Today there is no one standard and universal method, but there are also widely used methods such as computer databases, performance indicators, decision matrices, expert systems, cost analysis, failure analysis, cost-benefit analysis, and so on [6].

Failure analysis is the logical and systematic evaluation of a component through analytical observation and verification of good engineering practice. Depending on the defect, the researcher may perform a damage analysis using macroscopic and microscopic examination, analysis of the composite material, assessment of the supramolecular structure, and physical or mechanical testing. Both indestructible and destructive testing can be performed. Although the selection of experimental materials, such as testing and prototyping, is the most accurate for a specific design solution, due to the time required and the high cost of experiments, especially if more material needs to be considered, this quickly becomes impossible [7].

Root cause analysis (RCA) is one of the easiest and simplest ways to solve a problem in an engineering toolbox. It is used to identify the root causes of failures (defects, malfunctions) in engineering systems and to eliminate them [8].

This paper presents the theoretical foundations of the concept of four management tools and practically shows how they can and should be used for visualization, assessment, and further analysis of polymer materials during operation.

2 Research Problem

2.1 Definition of Criteria on Materials Selection in Product Development

In practice, the material engineer must control three factors that affect the cost of a product: the design of the components, the materials, and the manufacturing technology (Fig. 2) [9]. These factors are interrelated in that the creation of an element can affect what material is used, and both the design of the component and the material used to impact the manufacturing technology choice.

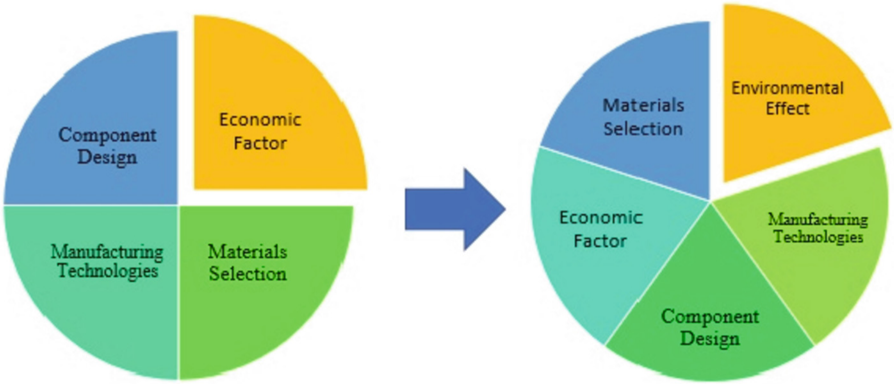


Fig. 2. Fundamental factors in sustainable manufacturing.

Some of the cost of a product component is related to its design (specification of size, shape, and configuration that affect the performance of the parts). Therefore, the design concept must consider the contribution of each component to the efficient operation of the entire system. The choice of materials with the appropriate combination of properties is based on the principle of affordability (least expensive). Therefore, a comparison is made of the cost of various competitive materials based on the price of each part. The choice of manufacturing process will be influenced by both the material selected and part design [10].

Materials play a crucial role in the "technology – economy – environment" scheme. So, the final product must be designed to have a minimal environmental impact. In addition, at the end of the service life, it must be possible to recycle the materials of the components, or at least dispose of them with minimal environmental impact [11].

2.2 Basic Methods of RCA for Development of Products or Services

Root cause analysis is used in lean production and helps to identify the root causes of the problem [12]. The main purpose of this method is to find the root cause of the problem through a series of questions: what happened, how it happened, and why it happened. This systematic approach to problem-solving is the root cause. It will help to develop solutions to the problem to prevent a recurrence. The general methodology of RCA is presented in Fig. 3.

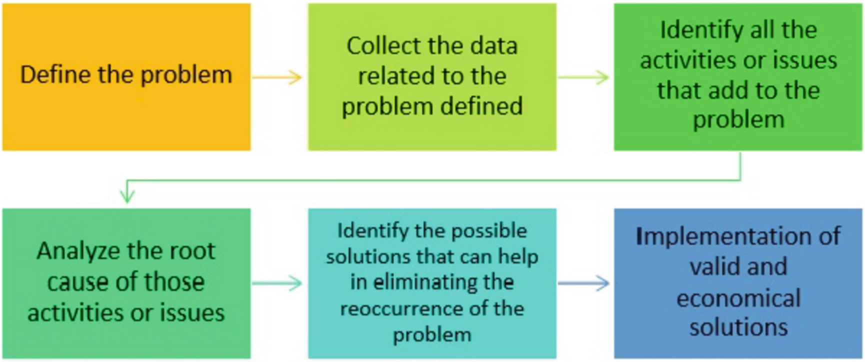


Fig. 3. Generalized RCA methodology.

RCA includes quite well-known and popular techniques for visualization, statistics collection, and quality analysis like 5 Whys, Fishbone diagram, FMEA method, Pareto method, etc. [13].

For our research, we settled on four of the most applied in the practice of materials science RCA tools: make a Fishbone diagram and analyze polymer composite defects by FMEA, make a house of the quality of polymer materials, and study the technique of LCA.

3 Results

3.1 Application of Cause and Effect Analysis for Defective Polymer Composite Material

The Cause and Effect Analysis helps identify the main factors that make the most significant contribution to the problem under consideration and prevent or eliminate their action. This method has already found its practical application in the diagnosis and defectoscopy of materials, in particular, to identify the leading causes of failure of the mounting bracket of the car bracket [14], chemical industry to assess the safety of spherical natural gas tank [15], biodiesel production technology [16], in automotive industries [17], etc.

The following steps illustrate the methodology of the Cause and Effect Analysis:

So, according to the main steps in Fig. 4, the materials science problem of obtained polymer composite blanks with low physical and mechanical properties was analyzed. These blanks are intended to manufacture various antifriction products by machining, including sliding bearings, O-rings of movable bearings and other friction units operating in air and liquid media, wet and dry gases in vacuum in the temperature range from minus 120 °C up to 260 °C. Blanks were obtained from a polymer composite, which does not meet the standard indicators (underestimated properties). The material of these blanks was Flubon 20 (80% polymer matric of PTFE and 20% carbon fibers) [18]. A Fishbone diagram was constructed (Fig. 5).

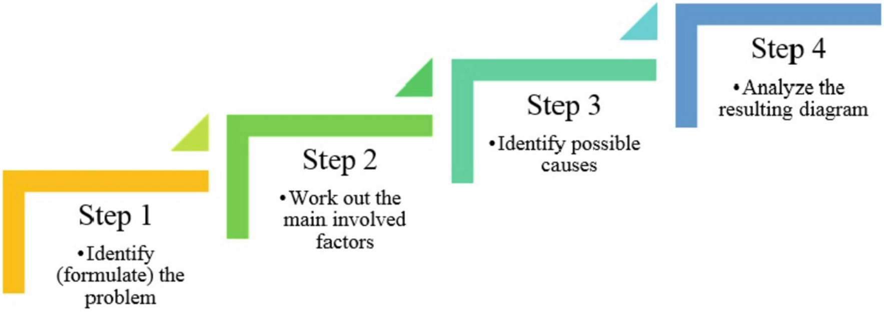


Fig. 4. Four main steps to applicate the tool of Cause and Effect analysis.

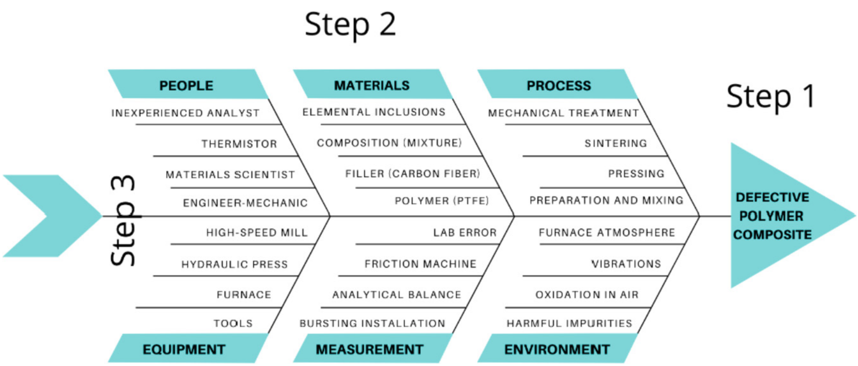


Fig. 5. Fishbone diagram of analyzing the defective polymer composite material.

A visual analysis of the machined turned surfaces of the test specimens revealed the following surface defects of the material surface: nonuniform distribution of carbon fiber in the polymer matrix, a patchy structure (alternating black and white spots), and the presence of cracks. During wear tests, an increase in temperature in the friction zone up to 200 °C was noted. It led to the seizure of the sample with the counter body. This phenomenon is associated with the material's low physical and mechanical properties (low density, uneven distribution of the filler in the polymer), confirmed by the tests carried out. All samples have a low elongation at break (30–100%). As a rule, this is a consequence of poor-quality mixing of the initial components – the presence of underground or coagulated fiber in the composition matrix.

The reasons were categorized into six key positions – person, method, material, mechanisms, control, and environment. The most significant causes of this problem were revealed with the employee's low qualifications and a violation of the mixing technology. In connection with the high responsibility of such products made from this material in the industry, it would be necessary to check the physical and mechanical properties of the entire batch. This problem would lead to the loss of material part, additional money and time, or replacement of the whole batch.

3.2 Investigation and Assessment of Macroscopic Polymer Composite Defects Using FMEA

At present, at least 80% of the processing of materials and technologies is carried out using the analysis of types and consequences of potential incompatibilities (FMEA methodology) [19]. The management of global companies widely introduces the types and consequences of potential incompatibilities for developing new designs and technologies, analysis, and planning of production processes and products [20]. This methodology makes it possible to assess the risks and potential damages from potential or existing defects from the initial design stage to create the finished product or its components [21].

In addition, the scope of the method covers all stages of the material life cycle, all technological processes, and trade [22]. The methodology of conducting any product/design FMEA involves following the steps (Fig. 6).

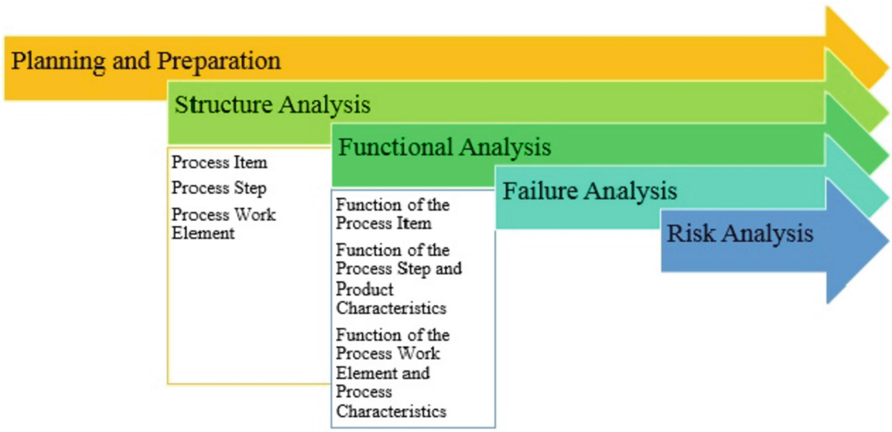


Fig. 6. The general methodology of the FMEA.

For example, FMEA was used to assess the macroscopic defects of polymer composite materials. External defects are various surface cracks, scratches, chips, chipping, etc.

At the macroscopic level, the following polymer composites characteristics were determined: uniform distribution of components; the number of components of the material, visually different in its structure; a geometric arrangement of the reinforcing filler; the geometric shape of the material components.

Finally, according to the FMEA methodology described in [23], it was assessed typically surface defects of polymer composites and established of permissible values for their characteristics. The results of the analysis are presented in Table 1.

Although surface defects slightly affect the mechanical properties of materials in the initial period of their occurrence, but they must be eliminated since the violation of the continuity of the outer surface of the material can further contribute to the penetration

Table 1. FMEA matrix.

Analyzed defect	Protentional causes	Possible consequences	S·O·D*, Risk assessment	Detection of the problem
Surface crack	Improper mode of forming the workpiece, high cooling rate. Shock effects during operation	Damage to the elements of the upper, inner, through detail part	$9 \cdot 3 \cdot 3 = 81$ defect is not critical (less than 100–120)	Determined visually, dependence on the size of the defect part, affected layers and direction of cracks
Scratch	Carelessness when removing parts from tooling and machining	Changes in the material composition in the cross section of the defect and physical and mechanical properties	$5 \cdot 1 \cdot 3 = 15$ are not large-scale	Determined visually, depth and width of the defect, orientation of the defect on detail
Inclusions	Getting foreign materials in the manufacture of prepreg		$5 \cdot 4 \cdot 4 = 80$ defect is not critical	Dimensions and thickness of the inclusion. Depth of occurrence
Chips, cuts and holes	Negligence when removing parts from equipment, transportation, storage, machining	They are voltage concentrators and reduce strength of composites	$4 \cdot 2 \cdot 2 = 16$ are not large-scale	Defect dimensions, width, depth
Local areas with high fiber content, matrix or pores	Non-compliance with the mode of formation, time and magnitude of the applied drop, heating rate	The degree of danger of these defects ultimately depends on the size, shape and location of the defect	$9 \cdot 4 \cdot 3 = 91$ defect is not critical	Determined visually, dependence on the size of the defect part, affected layers

* Notes: S (severity) – assessment of the most serious consequences of potential failure for consumers; O (occurrence) – the probability of specific causes and mechanisms of failure;D (detection) – assessment of the ability of the proposed management actions to detect this type of failure.

of aggressive media, which, ultimately, will significantly reduce the service life of the product.

Thus, this methodology can be successfully applied to all types of materials. It makes FMEA a universal management tool for assessing materials quality.

3.3 QFD Method

QFD is a flexible decision-making method that helps developers focus on the critical characteristics of a new or existing product or service from the perspective of an individual customer, market segment, company, or development technology [24]. The methodology results are clear diagrams and matrices that can be reused for future goods or services [25, 26].

In general terms, QFD consists of four matrices necessary to link the functions of the company and the needs of customers. These are product planning, part placement, process planning, and production planning schedules (Fig. 7). The initial QFD building process begins with a matrix that links customer needs to technical requirements and competitive information. This process is followed by a sequence of matrices that integrate the technical requirements into the design, operation and production system [27].

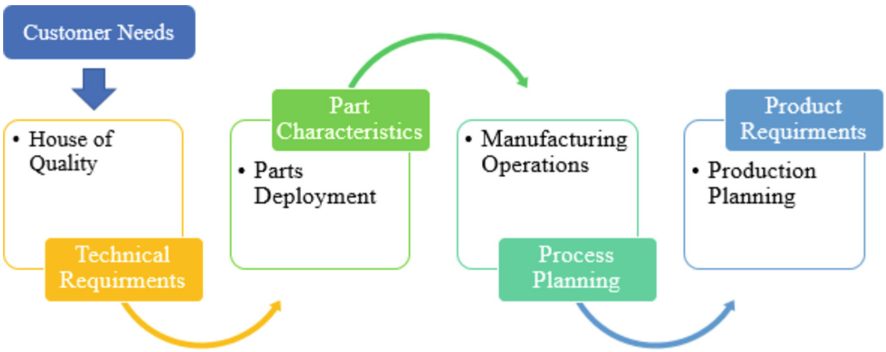


Fig. 7. Four QFD matrices.

The QFD quality function is deployed using a house-shaped diagram in which these matrices fit together (Fig. 1). It is named according to its form «House of Quality» (HOQ). The HOQ matrix is a basis that drives the entire QFD process and provides the tools to integrate customer requirements with technical requirements. The six building blocks of the HOQ matrix are described below (Fig. 8).

The central part of the house (3) is a table whose columns correspond to the technical characteristics (2), and the lines meet the requirements of the consumer (1). The level of addiction is noted in the cells, if any. The house's roof (5) represents information about the correlation between the technical characteristics. The left room (1) includes a column for the importance of customer requirements. The right room (4) consists of assessing the fulfillment of needs (from the consumer's point of view) for similar products on the market. The basement of the house (6) contains the results of the analysis of the technical

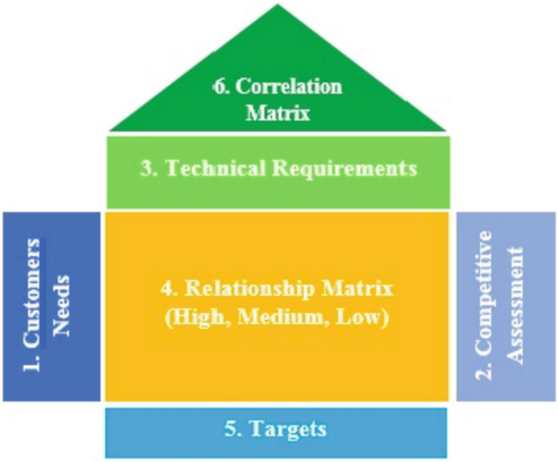


Fig. 8. House of quality matrix.

characteristics of competing products, the target values of the technical aspects of the products, estimates of the absolute and relative importance of the characteristics.

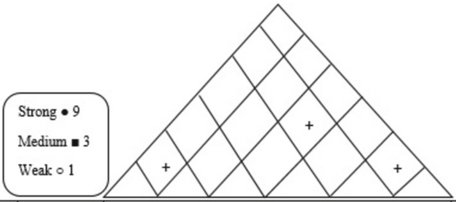
This methodology was used to carry out a quality analysis of developed polymer composites based on polytetrafluoroethylene with different fillers [28]. Figure 9 is shown for the most important indicators of products made of polymer composite material, where the links between requirements and characteristics are shown. The intensity of relationships is determined by the expert method.

The properties of products made of polymer materials are largely determined by the matrix's properties, the mixture's composition, and the modes of manufacturing processes. First, the parameters of the technological regime were ordered in order of importance (from 1 to 5) (Fig. 9, column 3). Then a connection was established between the technological mode parameter and characteristic (assign weights to strong, medium or weak links, respectively, 9, 3, 1). The transformation of customer requirements through QFD allows determining the relationship between requirements and characteristics. To determine the advantages of the developed materials in comparison with the industrial analogue, a comparison was made of the degree of consumer satisfaction (from 1 to 5).

Based on QFD analysis, it was found that the main parameters characterizing the required properties of the products under study are the strength at break, intensity of wear, and durability. The most significant factors affecting these parameters are material of polymer and filler and its technology of mixing. The influence of these parameters should be investigated to establish quantitative dependencies. The most priority technical characteristics were identified for further research and development of recommendations for improving quality.

3.4 LCA Analysis

Many of the industrial materials we consume come from non-renewable sources. These include most polymers that are used as raw materials for use, petroleum, and some



Row number	Requirement	Importance (1 to 5)	Characteristic						Competitiveness assessment					
			Strength at break	Relative elongation at break	Density	Intensity of wear	Coefficient of friction	Durability	Developed PTFE-composites [28]	Industry composite Flubon 20 [23]	Target value	Degree of improvement	Ponderability	Ponderability %
1	Type of polymer (matrix)	5	●	●	●	●	●	●	4	4	5	1,2	6,0	23,9
2	Type of filler	5	●	■	○	■	■	■	4	3	5	1,2	6,0	23,9
3	Mass ratio of polymer and filler	4	■	■	○	■	○	●	4	4	4	1,0	4,0	15,9
4	Mode of mechanical activation	3	●	●	○	●	○	■	3	0	4	1,3	3,9	15,5
5	The mixing time of the polymer with the filler	4	■	○	○	■	○	■	3	1	4	1,3	5,2	20,7
Absolute value			586,4	494,7	291,1	536,1	338,9	538,5						
Relative value, %			21	17,7	10,4	19,2	12,1	19,3						
Unit of measurement			MPa	%	kg/m^3	mm^3/N·m	–	h.						

Fig. 9. House of the quality matrix for polymer composites.

metals. These valuable resources are gradually depleted, which requires new solutions: increasing resources, processing new materials comparable in volume to the environment, increasing results or developing new processing technologies. From the point of view of the economics of production, the influence of the environment and environmental factors on sustainable production, the life cycle of the material "from the cradle to the grave" is more important than the entire production process [10].

Life cycle assessment (LCA) includes assessing potential aspects of the environment and possible aspects related to material (or product). It is a systematic set of procedures for the collection and study of the import and export of materials and energy and their direct impact on the environment (ISO 14040:2006 «Environmental management. Life cycle assessment. Principles and framework») (Fig. 10).

The assessment of the product life-cycle is based on a rather complex and comprehensive methodology for assessing the impact of products on the environment at all stages of its life-cycle: extraction of raw materials, production, use, repair, maintenance, transportation of the product at all stages, and ending with disposal or recycling of waste. The main steps of LCA analysis are summarized in Fig. 11.

An excellent example of LCA was used to compare a car as an example of an individual vehicle and a bus as an example of public transport [29, 30]. The material flow consists of the impacts in the production, use and handling of related wastes. Data were collected on all material flows generated by the car and bus during their operation. It turned out that the tension of the material of the bus is much higher than that of the car, 37 times higher. However, given that a bus travels 7.4 times longer in its lifetime than a car and carries 25 times more passengers than a car, the impact of a public bus per kilometer and per passenger compared to a car is about 5.0 times less.

Based on a comparative review of the environmental impact of different types of traditional bioplastics [31], note that environmental aspects of plastics production are

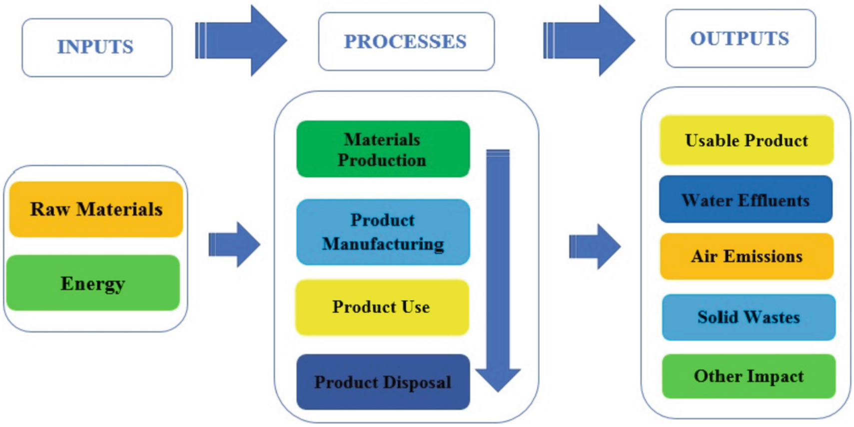


Fig. 10. Scheme of the life-cycle assessment of a product.

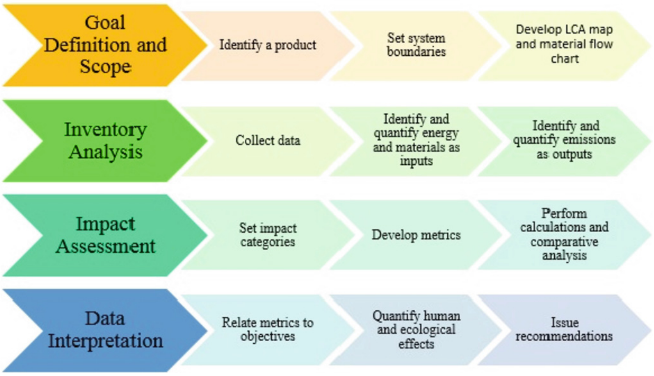


Fig. 11. Main key steps of a formal LCA study.

the negative impact on the atmosphere and protection of atmospheric air, as well as the formation of a few wastes in the production of plastic packaging. So, assessing the full life cycle developed polymer composites based on polytetrafluoroethylene with different types of fillers [28] seems to be an important and urgent task for future research direction.

4 Discussion

Cause and effect analysis visually display the relationship of the problem being investigated and the reasons that affect this problem; makes it possible to conduct meaningful research of the chain of interrelated causes affecting the problem; convenient and easy to use and understand.

The disadvantages of this quality tool include the difficulty of correctly determining the relationship between the problem under study. The causes of the problem under study are complex, i.e., part of a more difficult problem. The scope of analysis is quite broad, but it is often applied concerning developed products and related production processes.

The FMEA defines material properties that must be inspected, monitored, and controlled to ensure the part's reliability for the material is used to construct it. It is essential to understand that this type of analysis is intended to identify not the actual causes of probable failures but their manifestations, i.e., the types and forms of failures (failure modes).

The main advantage of QFD methodology over the other approaches is that it can be applied for processing qualitative and quantitative data and serve as a flexible framework that can be simplified, extended, and combined with other quality design and improvement techniques. Because this method provides both a score and a rank for each material, it helps designers better understand material selection issues by considering both the differences and similarities of alternative materials. Thus, it can be applied to any complex decision problem with many alternatives and quantitative criteria.

LCA of plastics and other structural materials play an important role in maintaining energy, saving resources, and saving money by preventing premature failures in an engineering component in a machine or equipment. LCA data on surface engineering materials improve the life cycle of a design component, increasing energy efficiency, sustainability and rejecting global temperature rise.

But LCA is applicable only as its data. Therefore, the data used to complete the life-cycle analysis must be accurate and up to date. When comparing different life-cycle analyses, equivalent data must be available for the product or process in question. If one product has much higher data availability, it may not be fair compared to another product with less detailed data. The importance of data is an ongoing challenge for life-cycle analysis. Thanks to globalization and the rapid pace of research and development, new materials and production methods are constantly being introduced to the market. It makes using up-to-date information very important and very difficult when performing LCA. If the LCA results are correct, the data must be up to date; however, the data collection process takes time. If the product and associated processes have not changed significantly since the last LCA data collection, the reliability of the data is not an issue. This paper will be useful for materials science and manufacturing engineers to understand the theoretical foundations of the concept of main management tools and practice using them with your own examples.

5 Conclusions

Cause and effect analysis turned out to be the easiest to understand and implement a method from RCA. To work with the Ishikawa diagram, we can easily involve students in practicing using management tools at the training stage.

QFD and FMEA, used as quality tools in composite materials design, can greatly improve development efficiency, leading to systematic design, material selection, and manufacturing.

The main LCA aim is to highlight the phases of the life cycle that have a strong impact on the environment and provide information for the product design process to improve environmental performance. This method is the only way to objectively determine which materials are environmentally friendly and which ones only seem to be.

Further research is related to the practical implementation of each of the described methods for solving various materials science problems of choosing materials. It is also planned to develop a prototype of the complex methodology (an expert system) based on multi-criteria decision-making (MCDM) system for materials selection in product development.

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References

1. Johnson, N.S., et al.: Invited review: machine learning for materials developments in metals additive manufacturing. Addit. Manuf. **36**, 101641 (2020). https://doi.org/10.1016/j.addma.2020.101641
2. Jahan, A., Edwards, K. L., Bahraminasab, M.: Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design, 2nd edn. Butterworth-Heinemann, Oxford (2016). https://doi.org/10.1016/B978-0-08-100536-1.00013-8
3. Wojciechowski, S., Przestacki, D., Chwalczuk, T.: The evaluation of surface integrity during machining of inconel 718 with various laser assistance strategies. MATEC Web of Conf. **136**, 01006 (2017)
4. Dobrotvorskiy, S., Balog, M., Basova, Y., Dobrovolska, L., Zinchenko, A.: Concept of the software for materials selection using .NET technologies. In: Tonkonogyi, V., et al. (eds.) InterPartner 2019. LNME, pp. 32–43. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-40724-7_4
5. Rahim, A.A., Musa, S.N., Ramesh, S., Lim, M.K.: A systematic review on material selection methods. Proc. Inst. Mech. Eng., Part L: J. Mater. Des. Appl. **234**(7), 1032–1059 (2020). https://doi.org/10.1177/1464420720916765
6. Trojanowski P.: Comparative analysis of the impact of road infrastructure development on road safety–a case study. Scientific Journals of the Maritime University of Szczecin 23–28, (2020). https://doi.org/10.17402/436
7. Jansen, J.: Root Cause Analysis: Success in Failure. Plastics Engineering, http://read.nxtbook.com/wiley/plasticsengineering/julyaugust2014/rootcauseanalysissuccessinfail.html. Accessed 10 Oct 2021
8. Wojciechowski, S., Twardowski, P.: Tool life and process dynamics in high speed ball end milling of hardened steel. Proc. CIRP **1**, 289–294 (2012)
9. Ashby, M.: Materials Selection in Mechanical Design. 4th edn. Butterworth-Heinemann, Oxford. (2011). https://doi.org/10.1016/B978-1-85617-663-7.00024-2
10. Callister, W.D., Jr., Rethwisch, D.G.: Materials Science and Engineering: An Introduction, 10th edn. Wiley, USA (2018)
11. Djassemi, M.: A computer-aided approach to material selection and environmental auditing. J. Manuf. Technol. Manag. **23**(6), 704–716 (2012). https://doi.org/10.1108/17410381211253290
12. Mahto, D., Kumar, A.: Application of root cause analysis in improvement of product quality and productivity. J. Ind. Eng. Manag. (JIEM) **1**(2), 16–53 (2008). https://doi.org/10.3926/jiem.v1n2.p16-53

13. Doggett, A.M.: Root cause analysis: a framework for tool selection. Qual. Manag. J. **12**(4), 34–45 (2005). https://doi.org/10.1080/10686967.2005.11919269
14. Dondapati, S., Trivedi, M., Dondapati, R.S., Chandra, D.: Investigation on the mechanical stresses in a muffler mounting bracket using root cause failure analysis (RCFA), finite element analysis and experimental validation. Eng. Fail. Anal. **81**, 145–154 (2017). https://doi.org/10.1016/j.engfailanal.2017.08.010
15. Luo, T., Wu, C., Duan, L.: Fishbone diagram and risk matrix analysis method and its application in safety assessment of natural gas spherical tank. J. Clean. Prod. **174**, 296–304 (2018). https://doi.org/10.1016/j.jclepro.2017.10.334
16. Kaščak, J., et al.: Design of an atypical construction of equipment for additive manufacturing with a conceptual solution of a printhead intended for the use of recycled plastic materials. Appl. Sci. **11**, 2928 (2021). https://doi.org/10.3390/app11072928
17. Xu, Z., Dang, Y., Munro, P.: Knowledge-driven intelligent quality problem-solving system in the automotive industry. Adv. Eng. Inf. **38**, 441–457 (2018). https://doi.org/10.1016/j.aei.2018.08.013
18. Budnik, O.A., Sviderskii, V.A., Budnik, A.F., Berladir, K.V., Rudenko, P.V.: Composite material for chemical and petrochemical equipment friction assemblies. Chem. Pet. Eng. **52**(1), 63–68 (2016)
19. Sharma, K.D., Srivastava, S.: Failure mode and effect analysis (FMEA) implementation: a literature review. J. Adv. Res. Aeronaut. Space Sci. **5**(1&2), 1–17 (2018)
20. Petrescu, L., Cazacu, E., Petrescu, M.-C.: Failure mode and effect analysis in automotive industry: a case study. Sci. Bullet. Electric. Eng. Faculty **19**(2), 10–15 (2019). https://doi.org/10.1515/sbeef-2019-0014
21. Mascia, A., et al.: A failure mode and effect analysis (FMEA)-based approach for risk assessment of scientific processes in non-regulated research laboratories. Accred. Qual. Assur. **25**(5–6), 311–321 (2020). https://doi.org/10.1007/s00769-020-01441-9
22. Antosz, K., Pasko, L., Gola, A.: The use of artificial intelligence methods to assess the effectiveness of lean maintenance concept implementation in manufacturing enterprises. Appl. Sci. **10**, 7922 (2020). https://doi.org/10.3390/app10217922
23. Rudenko, S., Berladir, K., Trojanowska, J., Varenyk, S., Shvetsov, D., Kravets, V.: Application of FMEA for assessment of the polymer composite materials quality. J. Eng. Sci. **8**(2), B12–B18 (2021). https://doi.org/10.21272/jes.2021.8(2).b3
24. Kazemzadeh, R.B., Behzadian, M., Aghdasi, M., et al.: Integration of marketing research techniques into house of quality and product family design. Int. J. Adv. Manuf. Technol. **41**, 1019 (2009). https://doi.org/10.1007/s00170-008-1533-2
25. Prasad, K., Maity, S.R., Chakraborty, S.: Quality function deployment-based expert system for materials selection. Int. J. Mater. Sci. Eng. **4**(2), 80–93 (2016). https://doi.org/10.17706/ijmse.2016.4.2.80-93
26. Mayyas, A., et al.: Using quality function deployment and analytical hierarchy process for material selection of body-in-white. Mater. Des. **32**(5), 2771–2782 (2011). https://doi.org/10.1016/j.matdes.2011.01.001
27. Bhattacharyya, O., Chakraborty, S.: Q-analysis in materials selection. Decis. Sci. Lett. **4**(1), 51–62 (2015). https://doi.org/10.5267/J.DSL.2014.9.001
28. Berladir, K., Gusak, O., Demianenko, M., Zajac, J., Ruban, A.: Functional properties of ptfe-composites produced by mechanical activation. In: Ivanov, V., et al. (eds.) DSMIE 2019. LNME, pp. 391–401. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-22365-6_39
29. Jacyna, M., Semenov, I.N., Trojanowski, P.: The research directions of increase effectiveness of the functioning of the RSA with regard to specialized transport. Arch. Transp. **35**(3), 27–39 (2015). https://doi.org/10.5604/08669546.1185181

30. Starzyńska, B., et al.: Requirements elicitation of passengers with reduced mobility for the design of high quality, accessible and inclusive public transport services. Manag. Product. Eng. Rev. **6**(3), 70–76 https://doi.org/10.1515/mper-2015-0028
31. Chernysh, Y., Balintova, M., Roi, I., Demcak, S.: Polymer materials: bibliographic data analysis and trend detection. Proc. Environ. Sci. Eng. Manag. **8**, 555–563 (2021)