sustainability

MDPI

Article

Implementing Concurrent Engineering and QFD Method to Achieve Realization of Sustainable Project

Lidija Rihar and Janez Kušar *

Faculty of Mechanical Engineering, University of Ljubljana, SI-1000 Ljubljana, Slovenia; lidija.rihar@outlook.com
* Correspondence: janez.kusar@fs.uni-lj.si

Abstract: In this paper, we present the impact of concurrent engineering strategies, methods, and tools on product sustainability. Concurrent engineering can be used to achieve the primary goals of a product realization project: lower costs, shorter times, high quality, and increasing value. Currently, it is important that new products also meet product sustainability goals, such as economic, environmental, and social goals. The sustainability of a product can be influenced the most in the early stages of product development, so in this paper, we present a customized quality function deployment (QFD) method called the house of sustainability, which translates sustainability requirements into technical solutions for a product. A seven-step process for implementing a sustainable product realization project is also proposed, in which the house of sustainability is one of the most important tools. The proposed process is illustrated with an example of a concurrent product realization project in engineering to order production.

Keywords: concurrent engineering; product sustainability; production sustainability; new product development; QFD

Citation: Rihar, L.; Kušar, J. Implementing Concurrent Engineering and QFD Method to Achieve Realization of Sustainable Project. *Sustainability* **2021**, *13*, 1091. https://doi.org/10.3390/su13031091

Academic Editor: Reza Kiani Mavi
Received: 16 December 2020
Accepted: 18 January 2021
Published: 21 January 2021

1. Introduction

Sustainability has lately become one of the key features of new products. Sustainability implies product properties that characterize it from the idea, through development, production, use, and maintenance, to the end of the life of the product (disposal). Sustainability means that the product not only fulfills its basic purpose, i.e., technical function, but that the product's properties, in terms of social (including political), environmental, and economic dimensions, are important as well [1,2]. This is particularly important because the goal of manufacturers is to make and sell as many products as possible on the market and thus generate as much profit as possible. At the same time, they want to manufacture products at the lowest possible cost, regardless of the negative impacts that the production of the product has on the environment, both during production and during the use of the product.

Today, we can buy a cheap product in a store or online, e.g., a household appliance, the service life of which is relatively short due to low quality and cheap integrated materials; then, that product is discarded because the cost of its decomposition would be too high in relation to its price. For this reason, many products are discarded on a daily basis, which has at least two detrimental impacts: (1) natural resources were used to manufacture the product, and (2) the product was discarded, and the environment burdened.

However, the practice described above does not only apply to consumer products but, unfortunately, also to the production of industrial products and facilities. In recent years, this problem has been seriously addressed in the scientific literature and by the governments and politicians of most developed countries, which is also encouraging. In 2015, the United Nations Assembly adopted the resolution transforming our world: the 2030 Agenda for Sustainable Development [3]. Both the European Union and Slovenia pay much attention to the field of sustainability in the documents of long-term development of the economy and the environment [4,5].

The indicated guidelines for sustainable development can be implemented in products/services only with a systematic approach in all phases of the product life cycle, from design to decomposition. The system of continuous sustainable product improvements, as well as responsible environmental management, gives companies a competitive advantage and greater added value of products with less impact on the environment. A systemic approach to sustainable product development includes economic and social impact on the entire product life cycle, and it is crucial to overcome traditional profit-based approaches to product development. The main goals of sustainable product development are the selection of environmentally friendly materials and technologies that rationally use natural resources and leave as little impact on the environment as possible. The consequence of such a decision is a lower consumption of natural resources (energy and materials) and emissions into the environment. In the short term, this mainly contributes to a cleaner environment, but in the long term, the economic and social impacts will also be visible.

At each stage of the product life cycle, there is a potential to reduce resource consumption and improve product efficiency. To achieve this goal, the 6 × RE method is used: REthink, REpair, REplace, REuse, REduce and REcycle [6,7]. The purpose and goals of the 6 × RE method are shown in Table 1.

Table 1. The purpose and goals of the 6 × RE method.

6 × RE Method	Purpose	Goals
REthink	Rethinking product performance and its functions.	More efficient product use and more functional product performance.
REpair	Is modular construction and easy assembly and disassembly of the product possible?	A simple product with simple components. Modular construction with a possibility of easy adjustments and changes.
REplace	Is it possible to replace harmful substances and their impacts at a particular stage of the product life cycle?	Reduction in harmful substances in the use of technologies, materials, implementation processes, and in the product use.
REuse	Is it possible to replace components with standard components or reuse existing ones?	Products that can be disassembled into individual components and replaced by new, more environmentally friendly ones.
REduce	Components designed as modules and usable for installation in several different products from each product family.	Use of cheaper processes with lower consumption of energy and materials throughout the product life cycle.
REcycle	Is it possible to use technologies and processes that have lower energy consumption?	Selection of recyclable materials.

Corporate social responsibility strategies are aimed at thinking more effectively about the product life cycle with the aim of accelerating the integration of environmental and social responsibility to address many pressing issues related to sustainable development and product life cycle. The system of sustainable product development must include all stakeholders in the entire logistics chain of product development, from suppliers, manufacturers, and subcontractors, to sales, users, and companies that will later decompose the product.

A comprehensive approach serves to exchange useful information and better focus on environmentally friendly material flow design in the product development phase, selection of the most suitable suppliers and procurement of materials with the lowest possible environmental impact, selection of technology with lower energy consumption and minimum negative impact on the environment, easier waste management, and implementation of recycling and reuse processes.

A system of continuous improvements in sustainable development and product life cycle can also be a good and effective practice of managing the entire supply chain and product life cycle in a broader sense, as communication and cooperation between all stakeholders establishes a link between demand, manufacturers, and market supply. In the long run, the market will only include the providers who will produce products that meet the standards of a sustainable, environmentally friendly product (as organic food in nutrition).

The paper will discuss the issue of sustainability in the case of new product development, which will be basically an existing product that will be upgraded with as many elements of sustainability as possible in all phases of the product life cycle (idea, development, manufacture, use, and disposal). As product development is always limited in time and cost, companies usually opt for concurrent product development, but we know that the greatest impact on the course and quality of product development is in the initial stages of product development [8]. Therefore, it is necessary to introduce the aspect of sustainability at the beginning of product development and only supplement the sustainable component in all subsequent stages of development.

Therefore, requirements for product sustainability represent important input requirements to be met by a new product. Quality function deployment (QFD) is a method in which, at the beginning of the development of a new (or changed existing) product, input requirements, which we call the "voice of the customer" who will use the product, are searched for and linked to the technical characteristics of the product.

The use of the QFD method [9–12] frequently appears in the literature dealing with sustainable product development. Our paper will propose a method for searching influential sustainability parameters (social, environmental, and economic) in the development of a new product that should meet the sustainability criteria, with the help of the adapted QFD, and link them with technical solutions to the product, individual components, processes, production, and maintenance, including product decomposition.

The characteristics of the product and its sustainability can be influenced the most in the early stages of its development, so in this paper, we propose a customized QFD method (called the house of sustainability) that can link product sustainability requirements with technical solutions in product realization. The distinctive feature of the proposed method is that when we evaluate the relationship between product sustainability requirements and technical solutions, we also consider whether the relationship has a positive or negative influence on technical solution or requirements. Based on the house of sustainability, we can determine which technical solutions contribute most to the sustainability of the product in terms of impact, performance, and cost-effectiveness.

The process of using a customized QFD in a concurrent product development project will be illustrated by the case of the development of the Kaplan turbine runner.

2. Literature Review

2.1. Sustainability and Product Development

In terms of sustainability, two major groups of publications appear in the literature. The first one refers to sustainable development from the point of view of the environment and the use of different types of energy sources, both from the point of view of production and mass consumption. In this group, most papers refer to the use of different energy sources for environmental sustainability [13,14].

The second group of publications, which is more important for our paper, relates to the development, production, and use of products, i.e., the sustainability of production systems and processes in which products are created and which determine product properties that affect a product's durability throughout the life cycle.

New product development and production sustainability has become a modern strategy that has received great acceptance and support in the world, but unfortunately, it is still insufficiently applied in practice [15]. The reason, in fact, may be that the companies still assess the development and production of products in terms of costs and profits. In order to enforce the principles of product and process sustainability, it is necessary to invest capital in research, which can provide an answer as to which materials and solutions can be used on the product to become environmentally friendly and, at the same time, meet social and economic criteria.

2.2. Sustainability and Quality Management

There are many articles in the literature about the link between sustainability and QFD. The model proposed in [15] by the authors of the paper is already based on three-dimensional QFD (customer requirements, environmental requirements, and technical solutions) and on concurrent product development that allows reduction of the time to market.

Otero et al. [16] showed methods for analyzing production system sustainability. They pointed out that the production of today faces three important problems: (1) pollution and waste problems, (2) consumption of nonrecyclable resources (oil, for example), and (3) rapid growth in the world population (which implies a growth in demand for both production and consumption). They pointed out that the sustainability of production systems is already based on three pillars or standards: Quality Management (ISO 9000) supporting economical sustainability, Prevention Management (OHSAS 18000) supporting social sustainability, and Environmental Management (ISO 14000) supporting environmental sustainability.

In his paper [17], Kun-Mo Lee pointed out that products as well as services consume natural resources and cause emissions into the environment. He therefore proposed two synonyms: an eco-design, which is a sustainable design, and an eco-product, which is a sustainable product. He emphasized that the implementation of sustainable production and the manufacture of sustainable products must be based on life cycle thinking on the entire supplier or value chain, i.e., not only product development and manufacturing processes but all upstream (natural resources, material, component manufacturing) and downstream processes (distribution, use, end-of-life of product). He put special emphasis on the integration of environmental aspects into product development (design). To this end, he proposed the use of environmental quality function deployment for sustainable products as a possible application of the well-known QFD, especially in the early stages of product development and, consequently, in the later stages of product and process development, wherein all four QFD development phases can be used [18].

In [9], Lin et al. linked the QFD and the analytical network process, enabling the creation of a powerful decision support tool based on the interdependence between different criteria and associated attributes. A similar decision support tool that is also a combination of ANP and QFD was proposed by Lam et al. [10]. Therefore, the correct choice of raw materials and suppliers (upstream components) is important for sustainable product production because they must also respect and regulate the principles of sustainability. Yazdani [12] et al. suggested linking QFD to the MCDM (multicriteria decision-making method) to select suppliers who meet the green supplier criteria. Dai and Blackhurst [18] noted the importance of the role of suppliers, particularly in phases 2 to 4 of a further QFD development, complementing QFD with the analytical hierarchy process (AHP).

Madzik et al. [19] claimed that QFD is one of the most popular tools for ensuring expected quality, even when used in the earliest stages of product development. To determine the importance of customer requirements, they proposed a method based on the Kano model extended with other relevant methods to improve the evaluation of technical attributes in QFD. Singh et al. [20] proposed the integration of a technique for order of preference by similarity to the ideal solution (TOPSIS) and QFD. With this integration, the score calculation of QFD can be greatly improved.

As can be seen from the previous literature review, most authors believe that product quality depends on the quality of the whole logistics chain of product development. Therefore, Zimon et al. [21] proposed a standardized management system that allows improvement of the quality of the whole sustainable supply management processes, of course taking the quality standards ISO 9001 and ISO 14001 into account [22].

Lindov et al. [23] argued that the use of QFD can affect the entire product life cycle from production to distribution to end-of-life processes. Masui [24] also addressed the entire product life cycle and proposed the term clean production, which aims to achieve the lowest possible environmental impact and maximum eco-efficiency.

Rahini et al. [25] proposed the integration of design for environmental impact matrix into QFD. By doing so, they want to emphasize that most of the characteristics of a sustainable product are determined at the product design stage. Masui et al. [26] also proposed a methodology for integrating environmental aspects into QFD so that both technical and environmental quality requirements can be considered simultaneously.

3. Methodology

Modern industry trends are consumer-oriented, which means that the customer wants to get a quality product as quickly as possible and at the lowest possible price. Of course, they want to be able to use the product for as long as possible, without excessive maintenance costs. In all this, however, it was forgotten in the past and unfortunately still is, even now, that every product is basically created from natural resources using energy that is also obtained in the environment. So, if the resources and energy are taken from the environment, the principles of sustainability teach that, after the use of the product, what has been taken away should be returned with the least possible consequences for the environment. This is currently also called circular economy, in which the product leaves as small of a carbon footprint in the environment as possible during its creation, use, and decomposition.

All of the above goals are the goals that we want to pursue in projects of concurrent development of sustainable products. The first part of the goals, i.e., a quality product, can be achieved in the shortest possible time, with the lowest possible costs, by upgrading the product development project management with strategies and methods of concurrent engineering. The goal is for the product to have the least possible impact on the environment and to leave the smallest possible carbon footprint in the environment. This can be achieved by integrating sustainability strategies, which are represented by related multidimensional indicators of sustainability (environmental, economic, and social).

3.1. Concurrent Engineering

Concurrent engineering is a managerial–operational approach aimed at improving product and process development, production, and product operation and maintenance. In such a process, participants from all professional fields necessary for the entire product development (marketing, design, process planning, production, and assembly) participate. Participants work together to achieve the set goals, constantly and directly exchanging data and information at all stages of the product life cycle.

The business strategy of concurrent engineering can be considered as an upgrade of the classic concept of project management of product development, in which the process of sequential engineering is replaced by concurrent engineering by introducing three important strategies: parallelism in process implementation, standardization, and process integration [27]. In line with the Industry 4.0 paradigm, the participation of participants in projects for the concurrent development of new products and the exchange of information between them must be based on modern information and communication technologies, especially in virtual environments due to globalization.

Concurrent engineering is derived from the track-and-loop principle [28], which envisages simultaneous implementation of smaller portions of works that are wholes in terms of contents and organization. These portions are called tracks. The tracks represent a complete whole of the work content (e.g., product development and design-related solution) and are interconnected in loops of concurrent engineering. The track-and-loop principle is based on the correct breakdown or decomposition of the work content, which is solved in project management by a work breakdown structure (WBS). To the greatest extent, the implementation of strategies of concurrent engineering and the track-and-loop principle depends on the participants in such a project. The efficient organization of project participants is in multidisciplinary, cross-functional teamwork, which is, according to Rihar [19], organized on two levels: as a project team responsible for project implementation, and working teams of loops responsible for carrying out activities in the concurrent engineering loops. The number of interactions between working team members depends on how many stages of product development are carried out simultaneously. It is usually decided to perform three stages of product development, or 3-T loops, at the same time (Figure 1).

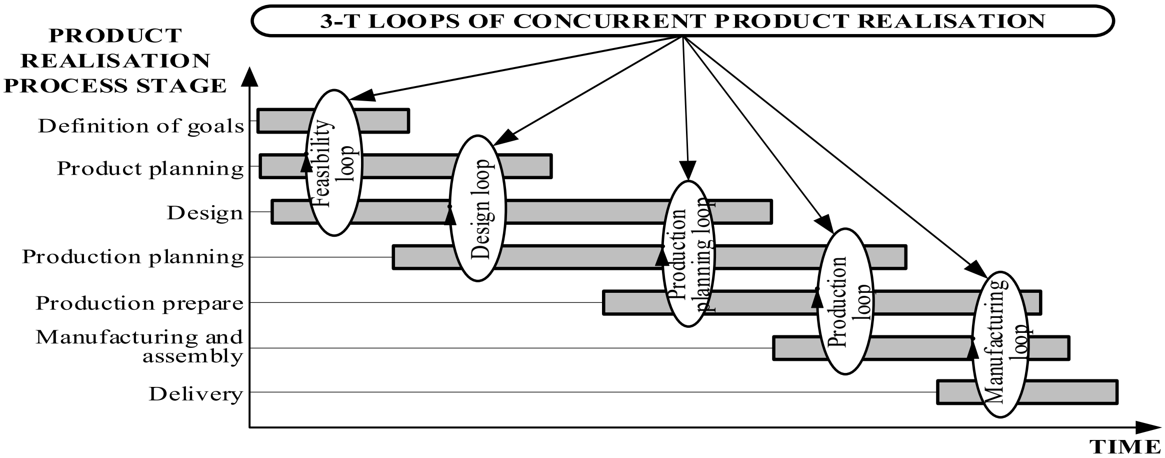


Figure 1. Track-and-loop principle of concurrent engineering.

The most important goals of concurrent engineering are: shortening the time of product development to its sale on the market, which can be achieved by parallel and interdependent implementation of activities; cost reduction, which is achieved by standardization and integration of processes, and elimination of shortcomings or nonconformities of the product and processes already in the early stages of product development (design, construction) and not only in the stages of industrialization, verification of the product and processes, or as late as in the stage of experimental or regular production [29,30].

3.2. *QFD and Sustainability*

When developing a new product, it is important that the input requirements are defined as precisely as possible from the beginning, i.e., the wishes of both the manufacturer and, above all, the users (customers) of the product. Therefore, the concurrent engineering methodology in the early stages of product development recommends the use of the QFD method, which allows one to qualitatively assess the input requirements and transform them into technical and other product properties. From the point of view of product sustainability, it is of course especially important that sustainability requirements are defined as early as the first phase of new product development, i.e., the definition of goals. This is especially confirmed by the fact that, in the beginning, it is not known how sustainability-related wishes and requirements will be put into practice. For example, we would like to replace oil in a product with water that is environmentally friendly, but we must first carry out appropriate research for such a solution and professionally justify such a decision.

In the literature, quite a few authors suggest the use of QFD in combination with other methods to analyze and find answers to input requirements for product sustainability throughout its lifetime [9–12]. The main difference between the QFD discussed in the literature and the proposed adapted QFD is that in the relational matrix, the values of the links between customer requirements and technical parameters (usually 9-3-1) are given, but here, we can choose whether the impact of the link is positive or negative. This, in turn, significantly affects the applicability of the QFD results.

The aim of all of the proposed methods is to effectively support decision-making to introduce changes that lead to product sustainability. In practice, it often turns out that managers do not opt for individual, more radical decisions because they do not have enough information about the proposed solutions and do not use the appropriate tool to support decision-making based on several criteria (multicriteria decision-making).

In the following, a custom-tailored QFD that was designed by the authors as a product life cycle management matrix and called the house of sustainability will be presented; through its use, the areas of sustainability—environmental, economic, and social—will be transformed into technical solutions and other product features. It will be determined which technical solution makes the greatest contribution not only to product sustainability but also to the economic impact of the envisaged solutions.

Since the matrices of relations and correlations are separated in the QFD, the importance of relations between input requirements (customer requirements) and technical solutions to the product can be calculated first and the correlations between individual technical solutions can be checked later. Our goal is to include the importance of correlations in the calculation of the importance of technical solutions. This is done by emphasizing, in the relational matrix with the sign + or −, whether a positive or negative impact is in place. To assess the importance of the relations, the standard scale is applied for QFD: 9 (high impact), 3 (medium impact), 1 (low impact), and 0 or blank (no impact).

In the custom-tailored QFD or the house of sustainability, the customer requirements are especially the requirements relating to sustainability, i.e., environmental, economic, and social, while technical and other requirements are the strategies for achieving product sustainability, as shown in Table 2.

Table 2. Sustainability-tailored quality function deployment (QFD), or a house of sustainability.

		Life Cycle Process—Strategies S_j, $j = 1, \ldots, m$						**Impact on Sustainability**	
				S_j					
Requirements R_i, $i = 1, \ldots, n$	**Impact Rate**	S_1	...	**Financial Imact x_F**	**Impact on Performance x_E**	...	S_m	**Financial Impact y_F**	**Impact on Performance y_E**
Requirement 1	w_1			x_{F1}	x_{E1}			y_{F1}	y_{E1}
:	:			:	:				
Requirement i	w_i			x_{Fij}	x_{Eij}			y_{Fi}	y_{Ei}
:	:			:	:				
Requirement n	w_n			x_{Fn}	x_{En}			y_{Fn}	y_{En}
Cumulative impact of strategy j			...	X_{Fj}	X_{Ej}	...		Y_{Fi}	Y_{Ei}

In the house of sustainability, the end-customer requirements have a different impact or weight w_i from the point of view of environmental, economic, and social aspects, so it was decided to weigh the customer requirements on a rating scale from 1 to 5 (1—very low impact, 2—low impact, 3—medium impact, 4—high impact, and 5—very high impact).

The relations in each strategy S_j to the customer requirements R_i are considered from two aspects: as a financial impact (x_{Fij}) and as an impact on the product sustainable efficiency and quality (x_{Eij}). The impact can be assessed with the classical QFD-specific scale (9, 3, 1), adding the sign of the influence + or −. The relations x_{Fij} and x_{Eij} may have the following values:

- 9—strong positive relation (very positive effect)
- 3—positive relation (positive effect)
- 1—poor positive relation (partially positive effect)
- 0—no relation (marked with blank)
- −1—poor negative relation (partially negative effect)
- −3—negative relation (negative effect)
- −9—strong negative relation (very negative effect)

In the following, the total financial impact X_{Fi} (Equation (1)) and the total impact on product efficiency and quality X_{Ei} (Equation (2)) of the strategies S_j on the customer requirements R_i can be calculated:

$$X_{Fj} = \sum_{i=1}^{n} w_i \times x_{Fij} \tag{1}$$

$$X_{Ej} = \sum_{i=1}^{n} w_i \times x_{Eij} \tag{2}$$

By calculating X_{Fj} and X_{Ej}, it can be determined which of the technical solutions has the greatest impact on customer requirements from economic, sustainability, and quality aspects of product development. This helps us in deciding which of the above strategies S_j will contribute the most to meeting customer requirements.

The right side of the custom-tailored QFD has two columns which are designed to calculate the total impact of customer requirements on product sustainability, wherein the impact is again split to the financial impact y_{Fi} (Equation (3)) on customer requirements R_i and the impact on the sustainability of product efficiency and quality y_{Ei} (Equation (4)) on customer requirements R_i:

$$y_{Fi} = \sum_{j=1}^{m} w_i \times x_{Fij} \tag{3}$$

$$y_{Ei} = \sum_{j=1}^{m} w_i \times x_{Eij} \tag{4}$$

Finally, the total financial impact of all voices of the customer on the product Y_{Fi} can be calculated (Equation (5)):

$$Y_{Fi} = \sum_{i=1}^{n} y_{Fi} \tag{5}$$

and the total voice of the customer on the sustainability of product efficiency and quality Y_{Ei}:

$$Y_{Ei} = \sum_{i=1}^{n} y_{Ei} \tag{6}$$

By analyzing the impact of individual customer requirements and the total impact of all customer requirements, the customer requirement that has the greatest impact on product sustainability and the relationship between financial and qualitative impacts of customer requirements on product sustainability can be determined. This is especially important if an existing product design is to be compared to a new product design that should meet the requirements for a sustainable product throughout its life.

From the point of view of the system of continuous improvement, the house of sustainability can provide support to the goals of ensuring the sustainability of products or services and the awareness of all stakeholders in product development for the necessary changes. At the same time, information is disseminated about products that include environmental, economic, and social aspects throughout their life cycle. With the help of the proposed house of sustainability (product life cycle management matrix), it is possible to assess the advantages and disadvantages of future scenarios and the impacts of different product implementation options in terms of efficiency, quality, and cost.

3.3. Systematic Approach for Sustainable Product Realization Project in Seven Steps

In order to carry out a sustainable product realization, a systematic approach of methodology has been proposed, carried out in seven steps (Figure 2). This methodology is a step-by-step approach that ensures the interplay between the development of knowledge about the environmental and social impacts of a product, market requirements, and the implementation of concrete product-oriented improvements. Important elements are:

- monitoring the performance of processes and products against defined goals and objectives,
- feedback and criticism from customers as important information for improving products and the product development process,
- determination of preventive and corrective actions for potential and actual nonconformities with requirements.

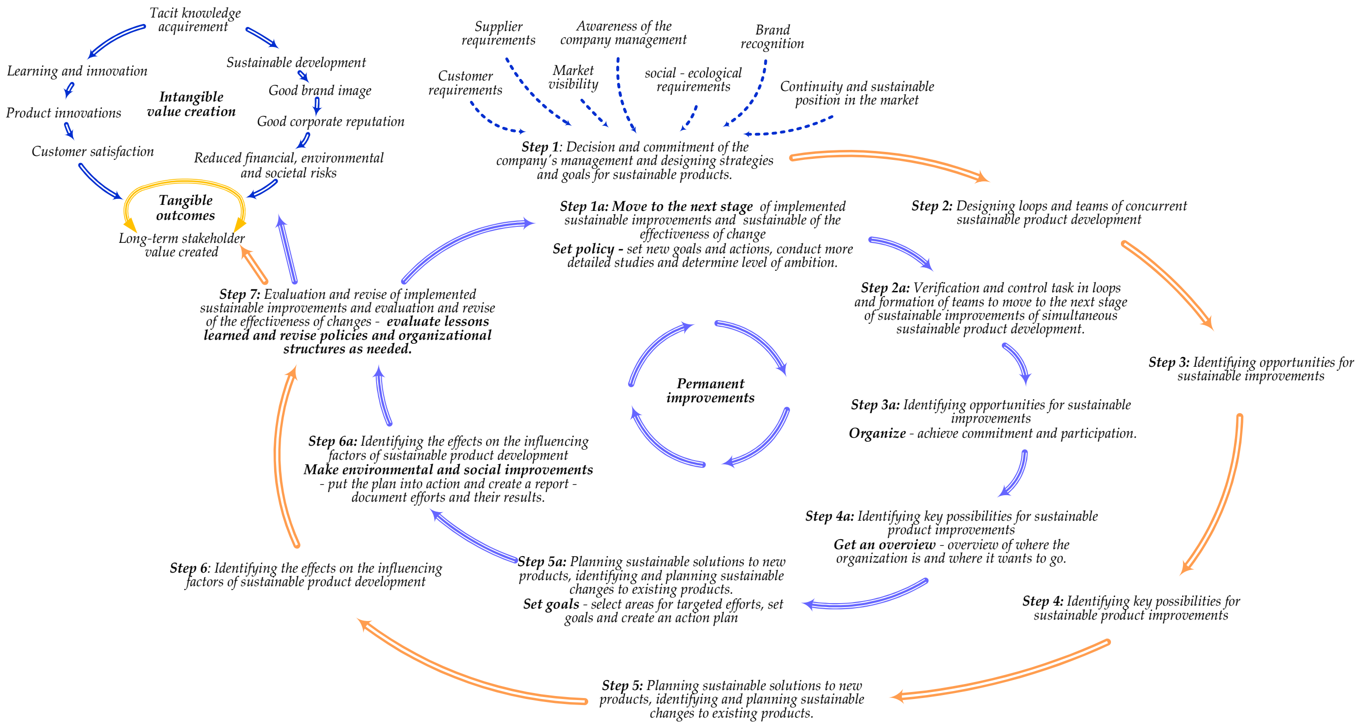


Figure 2. Systematic approach for sustainable product realization project in seven steps.

The proposed approach is suitable for developing a new product and for the reengineering of an existing product whose sustainability characteristics are to be improved.

There are several reasons to implement sustainable changes in product development, such as management awareness, brand awareness, customer requirements, market visibility, social–environmental requirements, continuity, and sustainable positioning in the market.

The decision to initiate changes in sustainable product development can help to evaluate the performance objectives and other criteria related to products, such as environmental and social impacts, stakeholders, market and trade conditions, and other management aspects such as quality, health, and safety, and from the perspective of sustainability, economic, and social aspects. The following factors are reviewed and assessed:

- The main environmental and social impacts in the life cycle
- In technology: Are there new technologies available, or are new technologies that can reduce environmental impacts being developed?
- Stakeholders in the production chain: Are there suppliers, retailers or others interested in collaborating on environmental and social initiatives?
- Within the industry: What are competitors doing in this area?
- The main consumer concerns and demands in the markets
- The social and environmental awareness of suppliers and customers
- The benefits of adding positive environmental and social attributes to product quality and value

To realize the project of sustainable product realization, a systematic approach to implementing sustainable product development in seven steps and two stages is proposed.

In the first stage, the first seven steps of the external circle are carried out, possibly only once. The steps of the external circle are:

Step 1: Decision and commitment of management and design of strategies and goals for sustainable products.

Step 2: Design of cycles and teams of simultaneous sustainable product development.

Step 3: Identifying opportunities for sustainable improvements.

Step 4: Identifying the key possibilities for sustainable product improvements.

Step 5: Planning sustainable solutions for new products and identifying and planning sustainable changes to existing products.

Step 6: Identifying impact on influencing factors of sustainable product development.

Step 7: Evaluate and revise the implemented sustainable improvements and evaluate and revise the effectiveness of the changes—evaluate lessons learned and revise policies and organizational structures as necessary.

The external cycle ends or begins with a review of the first external improvement cycle. Reviewing and addressing potential change of needs, goals, and other underlying systems, assessments, and changing environments provides an opportunity for continuous improvement in product performance. This is done by asking the following questions:

What went well and what did not?

What risks have been identified?

What preventive actions should be taken?

Were the objectives met?

How can the effort be improved?

Should more staff be involved in the initiative?

Should the effort be redirected?

Were the right tools and methods used?

What was the impact on revenue and customer requirements?

After such an assessment, a decision can be made to proceed to the next level. Based on the evaluation and revision of the implemented sustainable improvements, the effectiveness of the changes, and the development of knowledge gained from the implementation of the external cycle, an inner cycle that can be carried out at the higher level (even several times), which is further focused on achieving even better sustainable and environmental improvements can be started at this stage. By continually repeating the inner cycle, a system of continuous improvement that never ends is achieved. The steps of the inner cycle are:

Step 1a: Policy setting—setting new targets and measures, conducting more detailed studies, and determining the level of ambition.

Step 2a: Verification and control task in loops and formation of teams to reach the next level of sustainable improvements of concurrent sustainable product development.

Step 3a: Identify opportunities for sustainable improvements and organization—achieving commitment and participation.

Step 4a: Identify key opportunities for sustainable product improvements—get an overview of where the organization is and where it wants to go.

Step 5a: Plan sustainable solutions for new products, identify and plan sustainable changes to existing products, select areas for targeted efforts, set goals, and create an action plan.

Step 6a: Identify the impact on stakeholders of sustainable product development, make environmental and social improvements, put the plan into action, and prepare a report on the efforts and results.

Step 7a: Evaluate lessons learned and revise policies and organizational structures as needed.

The entire production chain should be included in a continuous improvement system (both in the external and internal cycle), involving producers, suppliers, manufacturers of materials and recycling, and other stakeholders in the production chains.

Based on the development of knowledge, it is possible to create long-term value for stakeholders with: (1) created intangible values, such as sustainable development, product innovation, silent acquisition of knowledge, market visibility, good brand, customer satisfaction, sustainable market position, a good reputation of the company, and reduced financial, environmental, and social risks, and (2) tangible results, such as generated long-term stakeholder assessments.

4. Example of Concurrent Project of Sustainable Product Realization

The use of the previously proposed methodology will be illustrated in a case of development of a more environmentally friendly product, which will be intended for installation in a hydroelectric power plant that produces green electricity. The company has more than 60 years of experience in the development and manufacture of turbines for hydropower plants, but they did not pay much attention to the development of environmentally friendly products in the past. However, they changed their mindset when they received an order from a Scandinavian client to develop and manufacture a Kaplan turbine, whereby the customer's signing of the contract was conditioned by requirements for a product that would be environmentally friendly throughout the operation of the hydropower plant. These requirements posed a particular challenge to the company's development engineers. Since the company used the QFD method in the past to identify customer requirements and wishes and to transform them into technical solutions to the product, they decided to include the requirements related to the product sustainability among the customer input requirements. In order to determine the financial and sustainability-related impacts of the product, they decided to create a house of sustainability according to the proposed methodology (Chapter 3) following the existing method of turbine construction and a new way to meet the customer requirements in terms of sustainability and an environmentally friendly product. Of course, the technical solutions that will ensure the product sustainability could include only those solutions, for which previous research has shown to be suitable and allow the operation of the turbine for at least 40 to 50 years.

To carry out the sustainable product realization project, a systematic approach that can be carried out in seven steps was selected. The proposed approach is suitable both for the development of a new product and for the reengineering of an existing product, the sustainability features of which are to be improved.

4.1. Step 1: Decision and Commitment of the Company's Management and Designing Strategies and Goals for Sustainable Products

Commitment to sustainable development and improvement at all stages of the product life cycle must be a decision and strategy of every company's management. The company's strategy must be long-term and realistic, and should, at the same time, include all departments of the company in sustainable development. The company strategy for commitment to product-oriented environmental management systems must include the following goals:

- commitment to continuous improvements in sustainability in the process of product design and development,
- improvement in the product life cycle outside the product production process by including its suppliers and customers in the strategy of sustainable product and process improvements, and
- promotion of sustainable products on the market as a competitive advantage.

4.2. Step 2: Designing Loops and Teams of Concurrent Sustainable Product Development

In the case of sustainable product development, in accordance with the strategy and guidelines of concurrent engineering, the concurrent implementation of activities is very important. For this purpose, the project team of sustainable product development determines the loops and for each loop creates working teams of concurrent sustainable product development (Figure 3).

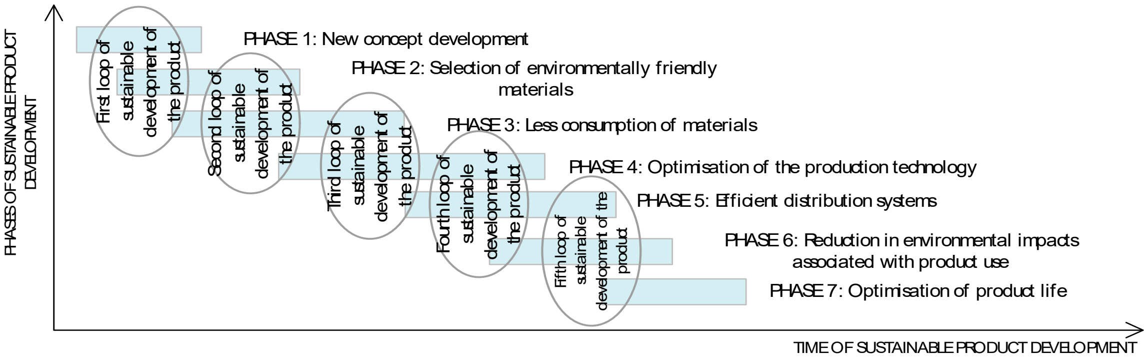


Figure 3. Loops of concurrent sustainable product development.

For the concurrent sustainable product development loops, the project team creates a template which includes the activities of individual loops and the relations between them. An example of such a proposal for concurrent sustainable product development is shown in Figure 4.

Compositions of the working teams included in the simultaneous sustainable development loops depend on the type of product. It is important that the working teams include those representatives of the company's organizational units and external participants who are involved in the implementation of loop activities, and that they are interconnected via modern information and communication systems that allow constant and direct exchange of information for coordinated work.

The project team of concurrent product development and the working teams of concurrent engineering loops are responsible for adhering to the principles of sustainable product development and especially for the results previously obtained with the house of sustainability. A team approach to work combined with synergy and integration of project stakeholders enables planning and coordination of various concepts, strategies, and tools.

Thus, sustainable product development requires teamwork and a concurrent approach, the result of which is product sustainability throughout the product life cycle. According to the principles of concurrent engineering, a working team is formed for each loop, each working team including representatives of organizational units of the company, as well as external stakeholders in the product development project, who significantly participate in the implementation of activities in the loop, e.g., customer, development, technology, procurement, production, logistics, and marketing representatives. The composition of the team of an individual loop depends on activities that run simultaneously and are informationally and functionally interdependent [29].

Using synergy, cooperation, and information integration, working team members of each loop provide ideas and proposals for solutions based on methods and tools of concurrent and sustainable development to achieve the goals and objectives of each loop. While the development process progresses along with the concurrent engineering loops, the goals and strategies that have proved important in the house of sustainability are gradually being realized. Each team works out environmental, social, and economical solutions in areas within its loop and within the assigned competencies. At the same time, the working teams of the sustainable product development loops have the task of complying with and coordinating product development with guidelines, laws, and regulations regarding environmental and sustainability-related requirements at all stages of the product life cycle. It is crucial that the strategy of sustainable product development is constantly supported by the company's management and that its measures constantly motivate all project participants.

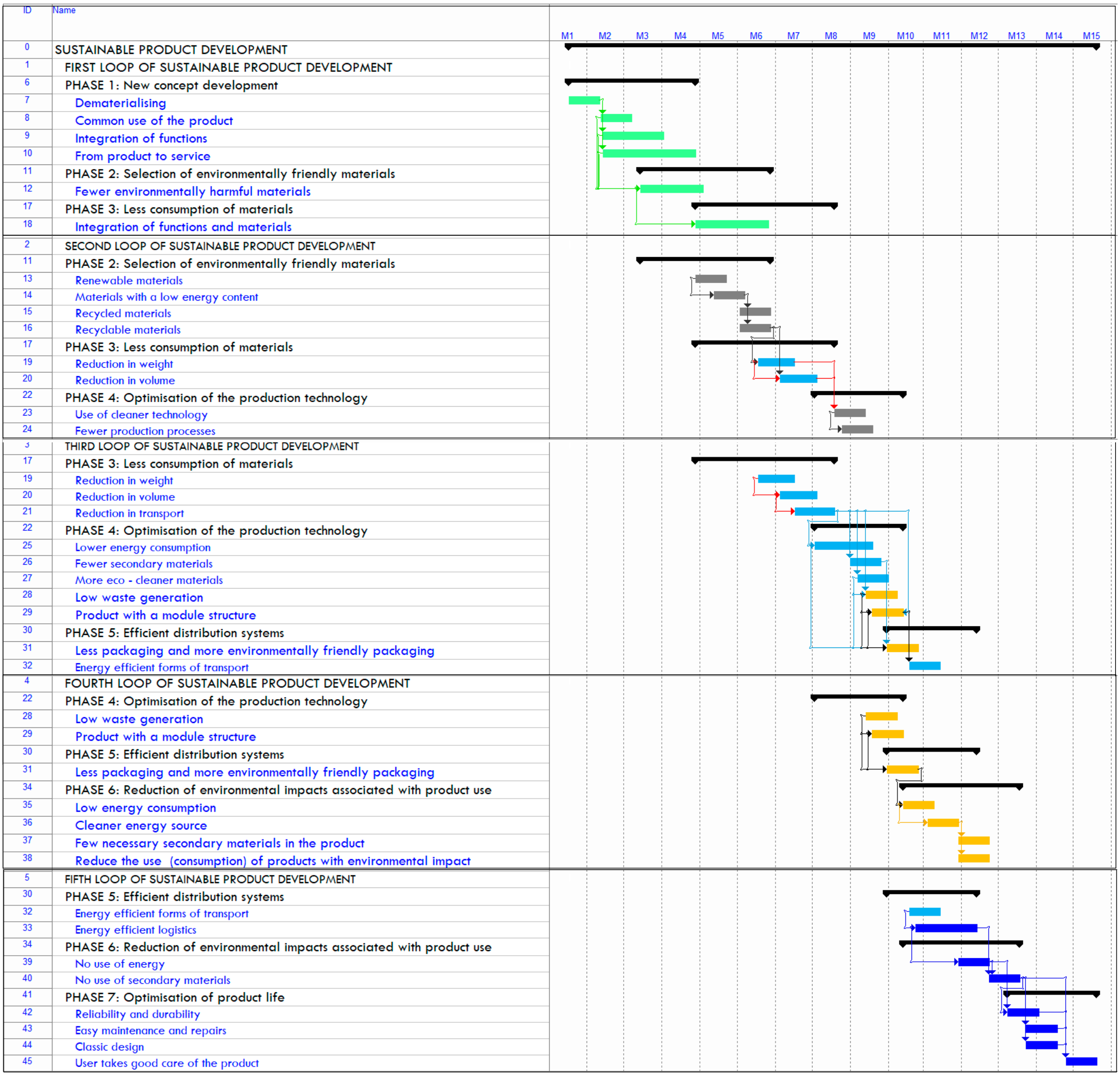


Figure 4. Gantt charts of loops of concurrent sustainable product development.

Sustainable product life cycle management is an opportunity to achieve environmental, ecological, health-related, and social goals while reducing costs. The goals of sustainable product development and system strategy pursued by the company are as follows:

- setting criteria for continuous improvement in products and processes by creating added value of products,
- increasing the potential for innovation and solutions to create sustainable products,
- identifying opportunities and risks in sustainable product development,
- strengthening competitive advantage through innovative solutions to designing products that have a low environmental impact,
- designing and planning the implementation of sustainable products by choosing cleaner technologies (eco-technologies),

- creating requirements for product recycling and production of new products from renewable raw materials,
- sustainable procurement of materials with lower environmental impact,
- sustainable production and distribution,
- a strategy for prioritizing funding for sustainable development projects,
- connecting all stakeholders in the procurement–production–supply chain to coordinate shared responsibility and risk related to environmental requirements and the reduction in environmental penalties,
- marketing sustainable products and increasing market share,
- building a brand of sustainable products and better market positioning.

The strategy of raising awareness of all stakeholders in the procurement–production–supply chain about the importance of reducing the content of hazardous substances in products has as important an impact on success as technical solutions and innovations. The integration of environmental and socioeconomic solutions into product development and design also encourages innovation to introduce new concepts in transforming the classic product development process into a sustainable one.

It is important that changes are introduced as improvements to existing product design and development processes. Therefore, there is no single approach to the concept of sustainable product and process development; each approach is tailored to each product, and only guidelines can be common, such as:

- identification of product functions and possibilities for improvement according to technical, environmental, and cost-related criteria
- identification of existing products to make them more sustainable by replacing environmentally harmful substances with harmless (or at least less harmful) ones
- selection of environmentally friendly technologies, and
- selection of degradable and more environmentally friendly materials with low environmental impact in the production, use, and decomposition

According to Figure 3, the principles of sustainable product development are mostly put into reality in the loops of sustainable concurrent product development.

Loop one of sustainable development, product concept development, must shape the conceptual design of a product with innovative and sustainable solutions that enable environmental, social, and economic improvements that are in line with implementation possibilities and legislation. The product concept provides guidelines for the entire production supply and value chain, i.e., outlines conceptual design solutions, plans the use of suitable materials, and selects the technology for the manufacture of the product and its decomposition. Loop one also sets the requirements for product recycling and production of new products from renewable raw materials.

Loop two of sustainable development, product development, is aimed at identifying, based on the solutions and guidelines of loop one, the possibilities of appropriate design solutions to the product, which will provide for the product's functionality and sustainability. It is important to incorporate such materials and components into the product that will be environmentally friendly while providing a quality and reliable product.

Loop three of sustainable development, process development, has the task to select, based on the requirements and guidelines of loop two, the most suitable technology for the manufacture of components and the entire product. Typically, the selection of technology for processing new environmentally friendly materials at least initially makes the whole process more expensive, mainly due to the lack of knowledge of the behavior and properties of materials and new technologies. The required changes in materials that have a favorable environmental impact also consequently affect the material procurement process, logistical requirements, and the search for potential new markets. The selection of technological processes must be based on the reduction in resource consumption and thus on the reduction in the environmental impact.

Loop four of sustainable development, implementation of the product creation process, has the task of identifying, based on the selected technologies and prescribed procedures from loop three, opportunities for possible improvements in manufacturing processes. Based on practical experience and good knowledge of the process, solutions are proposed that, on one hand, simplify the manufacturing process and reduce costs and, on the other hand, choose such solutions in production that make the greatest possible contribution to a clean environment.

Loop five of sustainable development, production and distribution, has the task of actively contributing to the reduction in resources, energy and waste, based on the requirements of the selected processes of loop four. It is also necessary to choose the ecological method of implementation. Product distribution in particular is often associated with high energy consumption and environmental pollution (road transport).

4.3. Step 3: Identifying Opportunities for Sustainable Improvements

In this step, an inspection of the existing product and its components is performed first. It is necessary to determine which changes and improvements can be carried out immediately to achieve product sustainability with the already known solutions and which are potential candidate solutions, which require prior research [31,32].

In the case of the Kaplan turbine, sustainable improvements must be aimed primarily at reducing the ecological risk in use and maintenance, because it is the Kaplan turbine that poses the greatest ecological risk of all water turbines. The Kaplan turbine uses a large amount of hydraulic oil for smooth operation, which poses a great ecological risk. In the case under consideration, the requirements for these changes were the client's/customer's explicit requirements.

To identify potential improvements that would meet the customer's requirements, all major Kaplan turbine systems were analyzed and all potential environmental risks identified. The main risk is the use of hydraulic oil. Then, the project team and experts from various fields had creative workshops to look for possible solutions to improvements and to solving the presented problem. Table 3 shows the analysis of all turbine systems and the potential risks of the old (existing) version, as well as proposals for changes in the new version.

Table 3. Overview of the main components of the Kaplan turbine and the possibilities of sustainable solutions.

Kaplan Turbine	Old Version	Options for Changes New Version
Runner	Operation with hydraulic oil (1200 L), which is very problematic for the environment and would have a very negative environmental impact in the event of a spillage	ECO-RUNNER Possibility of an oil-free version; oil is replaced by distilled water with viscosity-enhancing and lubrication additives
Guide vanes	No hydraulic oil in the guide vane	No changes necessary
Regulation system	Hydraulic oil operation (500 L)	No solution at the moment; suggestions for potential solutions have been made that need to be explored
Servo motors	Oil quantities to: GUIDE VANE $\Longrightarrow$ 2 × (500–600 L) RUNNER $\Longrightarrow$2 × (150–200 L) LOCKING MEMBERS $\Longrightarrow$ for: lifting of slide valves 1 × (50–150 L) lifting of a flap 2 × (50–150 L) Hydraulic oil operation total: (1450 to 1950) L	No feasible solution at the moment; suggestions for potential solutions have been made that need to be explored
Lubrication system	Hydraulic oil operation: (500 L)	No feasible solution at the moment; suggestions for potential solutions have been made that need to be explored
Bearings	Hydraulic oil operation: at least 3 × (500–600 L), total (1500–1800) L	No feasible solution at the moment; suggestions for potential solutions have been made that need to be explored
Total:	**Hydraulic oil: (6652–8452) L**	**(5452–7252) L of hydraulic oil + 1200 L of distilled water with viscosity-enhancing and lubrication additives**

Table 3 shows that currently only the Kaplan turbine runner can be improved, while the replacement of hydraulic oil with another agent on all other main turbine systems requires further investigation. The proposed solutions to the eco-runner are suitable not only for the Kaplan turbine but also for tubular and Francis turbines.

In any case, replacing the oil with distilled water with additives alone saves about 1200 liters of oil in the turbine, which represents 18% of the total required lubrication fluid. The results of the performed analysis represent a challenge for the researchers to replace the hydraulic oil partially or completely in other turbine systems.

4.4. Step 4: Identifying Key Possibilities for Sustainable Product Improvements

To identify the key possibilities for improvements to achieve product sustainability, the 6 × RE method is used to review the entire design, technology, and use of the product and to identify the possibilities of key sustainable changes in the implementation with appropriate solutions. Table 4 shows the identified key areas for improvement for the Kaplan runner.

Table 4. Identifying the areas for sustainable improvements in the Kaplan runner using the 6 × RE method.

6 × RE Method	Runner—New Version
REthink	no oil, no storage of hazardous substances, no transport of hazardous substances, ecological product—eco-runner
REpair	old and new versions—no difference no disposal and storage of hazardous substances,
REplace	replacement of oil and grease with distilled water with viscosity-enhancing and lubrication additives, which has a minimal environmental impact compared to hydraulic oil
REuse	the materials used can be recycled and reused if the materials are not impregnated with hydraulic turbine oil and grease
REduce	not possible due to the specific product structure
REcycle	easier recycling due to environmentally friendlier materials most material is recycled and reused (both liquid and metal)

4.5. Step 5: Planning Sustainable Solutions to New Products, Identifying and Planning Sustainable Changes to Existing Products

In order to plan a sustainable development of a new product or an improvement in the existing product, guidelines and legal requirements as well as impacts on the sustainability of the product life cycle throughout the supply–production–sales chain of the product must be taken into account. In sustainable product planning, the following must be taken into account:

- environmental impact and financial impact in product manufacture
- impact on the involvement of all stakeholders in the product supply–production–sales chain
- impact on the sustainable use of the product and the processes for product decomposition and recycling

Different methods and techniques shown in Table 5 are used to identify opportunities for improvement and to design possible solutions in different areas of the product life cycle.

Table 5. Overview of tools used in planning and identifying sustainable product improvements.

Areas of Sustainable Improvements	Methods Used in Sustainable Development
Environmental and sustainable impact	Environmental impact assessment Input–output analysis (IOA) Life cycle assessment (LCA)
Costs, benefits, and risks	Cost–benefit analysis (CBA) Life cycle costing (LCC) Risk assessment (RA)
Technologies and materials	Material input per unit of service (MIPS) Material and substance analysis (MFA)
Implementation and technologies	Production assessment (CPA) Material and flow analysis (SFA)
Product planning	Design for sustainability (DFS) Quality function deployment (QFD), Failure mode and effects analysis (FMEA) Design for manufacturing (DFM) Design for assembly (DFA) Design for manufacture and assembly (DfMA)
Energy consumption	Cumulative energy requirements analysis

For the case of the Kaplan eco-runner, Table 6 presents the solutions and improvements that were implemented using the methods and tools presented in Table 4.

Table 6. Changes that were made for the new version of the Kaplan eco-runner.

Runner	Changes—New Version for the Manufacturer
Structure	Remains unchanged: the structure must remain the same to provide power
Technology	It is changed and adapted due to: the use of new materials that have different machining properties and behave differently during machining, different behavior of materials in machining, casting, forging, welding different anticorrosion protection due to changed lubricating fluid
Stability of structural parts	It may change, but the same or better properties must be provided compared to the original materials. The materials should be tested in operating conditions by being installed into smaller turbines. The behavior of structural parts during operation, aging, renovation, or finishing needs to be determined.
Use of materials	It can be changed and adjusted due to different composition and properties of the material (the function of use remains the same)
Implementation and installation	It is changed and adapted due to: different composition and properties of the material changed technology and processing changed fluid (oil replaced by distilled water with viscosity-enhancing and lubrication additives) installation protocol remains the same
Warranty Period	Remains unchanged additional control; more frequent control and monitoring required

4.6. Step 6: Identifying the Effects on the Influencing Factors of Sustainable Product Development

The effects on the influencing factors of sustainable product solutions can be identified according to:

- feasibility, acceptability, and adequacy of the most appropriate solutions,
- potential for environmental and social improvement,

- the financial and economic impact of the implemented solutions.

Improved product features always also influence the customer's responsibility. The customer identifies the changes mainly in terms of the impact on the performance of the product, its quality and, of course, the selling price. Table 7 shows the identified impacts of changes in the new version of the Kaplan eco-runner.

Table 7. Impact of changes on the entire life cycle of the Kaplan eco runner.

Runner	Identified Changes—New Performance for the Manufacturer
Structure	Impact on performance: is changed by ≈10% technology and processing are changed and adapted the sealing system is changed Financial impact: the price increases (⇑30%) due to the use of new materials and the adjustment of the structure and sealing due to the replacement of hydraulic oil with distilled water with viscosity-enhancing additives
Technology	Impact on performance: is changed by ≈25% due to changed technology, the materials used, and processing Financial impact: the price decreases (⇓35%) - due to the use of distilled water with viscosity-enhancing additives, easier sealing compared to hydraulic oil
Stability of structural parts	Impact on performance: is changed by ≈10% due to the use of new materials, seals, and operating conditions (replacement of hydraulic oil with distilled water with viscosity-enhancing additives) Financial impact: the price increases (⇑ 10%) - due to the protocol, testing, and monitoring of the behavior of materials in operating conditions
Use of materials	Impact on performance: is changed by ≈20% due to the protocol of structural adaptations, technology, and processing Financial impact: the price increases (⇑ 25%) (at the beginning, due to the lack of knowledge about the properties and behavior of the material)
Implementation and installation	Impact on performance: is partially changed—adapted by ≈ 10% Financial impact: does not change and the price does not increase
Warranty period	Impact on performance: is partially changed—adapted by ≈20% Financial impact: the price increases (⇑ 10%) more frequent performance controls—monitoring

4.7. Step 7: Evaluation of Implemented Sustainable Improvements and Evaluation of the Effectiveness of Changes

In the last step, the positive and harmful effects of product development, manufacture and use are assessed in relation to the sustainable product development in terms of impact on the product efficiency and quality and the cost effect. The criteria for assessing the effects are implementation of the structure, use of materials, possibilities of technology selection, possibilities of production, and decomposition of the product after use.

The assessment of the positive and negative influencing effects of sustainable product development is performed using a predesigned template of the product life cycle management matrix, or the house of sustainability, the use of which on the Kaplan turbine runner is shown in Figure 5.

LIFE CYCLE MANAGEMENT PROCESS

IMPACT OF THE CYCLE PROCESS ON THE ELEMENTS OF SUSTAINABILITY

1 – very low impact
2 – medium low impact
3 – medium impact
4 – medium high impact
5 – very high impact

EFFECT OF LIFE CYCLE PROCESS ON THE ELEMENTS OF SUSTAINABILITY

(– 9) – very negative effect
(– 3) – negative effect
(– 1) – negative effect
(0) – no effect
(+ 1) – partially positive effect
(+ 3) – positive effect
(+ 9) – very positive effect

		RELEVANCE TO THE IMPACT ON SUSTAINABLE DEVELOPMENT	Life Cycle Process– PERFORMANCE												Life Cycle Process– CUSTOMER						IMPACT ON SUSTAINABLE PRODUCT DEVELOPMENT	
			PLANNING AND DEVELOPMENT		CONSTRUCTION SOLUTIONS		TECHNOLOGY SELECTION		MANUFACTURE OF COMPONENTS		ASSEMBLY AND INSTALLATION		INSTALLATION AND ASSEMBLY (ON THE FACILITY)		USE		RENOVATION OF VITAL PARTS		DECOMPOSITION OF MATERIALS– at the end of the product life			
			financial impact	impact on performance	financial impact	impact on performance	financial impact	impact on performance	financial impact	impact on performance	financial impact	impact on performance	financial impact	impact on performancea	financial impact	impact on maintenance	financial impact	impact on maintenance	financial impact	impact on maintenance	financial impact	impact on performance and an maintenance
OLD PERFORMANCE	IMPACT ON THE ENVIRONMENT	5	0	0	0	0	0	0	0	0	0	3	– 3	0	– 9	– 9	– 3	– 3	– 9	– 3	– 120	– 60
	IMPACT ON THE USE OF MATERIALS	2	1	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	– 1	– 1	2	4
	IMPACT ON HEALTH	5	0	0	0	0	– 1	1	– 1	0	0	– 1	– 1	–1	– 1	– 1	–1	–1	– 3	– 3	– 40	– 30
	IMPACT ON SAFETY	3	3	3	1	1	0	1	– 1	0	– 1	0	– 1	–1	– 3	– 1	–1	–1	– 3	– 1	– 18	3
NEW PERFORMANCE	IMPACT ON THE ENVIRONMENT	5	– 3	9	– 1	3	– 3	3	–3	3	– 3	1	– 1	9	– 1	0	9	9	– 1	3	– 35	200
	IMPACT ON THE USE OF MATERIALS	2	– 1	3	– 1	3	– 3	– 1	–1	–1	0	– 1	– 1	3	0	0	0	0	0	0	– 14	12
	IMPACT ON HEALTH	5	– 1	9	– 1	3	– 1	3	–1	0	0	3	– 1	3	9	9	9	9	– 1	3	60	210
	IMPACT ON SAFETY	3	– 1	3	– 3	9	– 1	1	–1	0	– 1	3	– 1	3	9	9	9	9	– 1	3	27	120
OLD PERFORMANCE			11	11	5	5	4	– 3	0	– 3	– 3	10	– 23	– 8	– 59	– 53	– 23	– 23	– 71	– 35	– 176	– 83
NEW PERFORMANCE			– 25	105	– 21	63	– 29	31	– 25	13	–18	27	–15	75	67	72	117	117	–13	39	38	542

Figure 5. Product life cycle management matrix, or a house of sustainability, for a Kaplan turbine runner.

5. Results and Discussion

Based on the implemented steps described in the previous chapter, the project team, together with experts in various fields of turbine development, created a product life cycle management matrix, or a house of sustainability, for the Kaplan turbine runner, which is shown in Figure 5.

The product life cycle management matrix, or the house of sustainability, which represents a QFD custom-tailored to sustainability requirements, was used to obtain an assessment of the technical solutions that could be used to minimize the environmental, ecological, and financial impacts associated with the runner in its life cycle. In the house of sustainability matrix in Figure 5, a sustainability analysis was performed for both the existing runner and a new runner that will meet the customer's product sustainability requirements.

The analysis of the house of sustainability for the Kaplan turbine runner showed the following:

1. The old version of the runner has a very negative impact on the product sustainability, both from the point of view of the implementation process and from the financial point of view. Structural solutions, the selection of materials, and the selection of technology all have a negative impact. As a result, this also has a very negative impact on the use, maintenance, renovation of vital parts, and decomposition at the end of the product's life.
2. The old version of the runner has a very negative impact on the environment, the health of the people, and thus on their safety. With the old version of the runner, there is a high risk of oil spillage into the environment. The built-in components of the turbine are immersed in oil and grease throughout their operation, which makes the materials more difficult to degrade. Every oil change is followed by a decomposition process, which is expensive and environmentally unfriendly, as decomposition produces toxic substances that can remain in the air, water, and soil and can have a very negative impact on living and, in the long run, on food production for people and animals. Degraded oil is often used as a fuel, which is again a great burden for nature and health. The storage of new and used oil requires special

facilities that prevent the oil from leaking into the environment. In addition, hydraulic oil is flammable; this poses an additional ecological risk.

3. The new version of the eco-runner has a very positive impact on the environment, safety, and health due to its being adapted to sustainability requirements. The new solution to the runner is slightly more expensive in development and production due to the use of new materials, technologies, processing and assembly. However, all these changes result in a very positive impact on operation, maintenance, renovation of vital parts, and decomposition at the end of the product's life. Therefore, the new version of the eco-runner has a very positive impact on the environment from both the implementation-related and financial points of view. Regarding the purpose and use of the product, there should be no major difference between the old and new versions.
4. Thanks to the use of new materials, structural adjustment, sealing, and the replacement of hydraulic oil with distilled water with viscosity-enhancing and lubrication additives, the eco-runner has a very positive impact on product sustainability from financial, environmental and social aspects. Even after use, the turbine components remain as they were installed (except for the expected wear), as the materials are not impregnated with oil and grease. In the case of spillage of distilled water (water does not burn) into the environment, this poses almost no ecological risk to safety and the environment.

Figure 6a shows a comparison between the financial impacts, and Figure 6b shows a comparison between the impact on performance for the old and new versions of the Kaplan turbine runner.

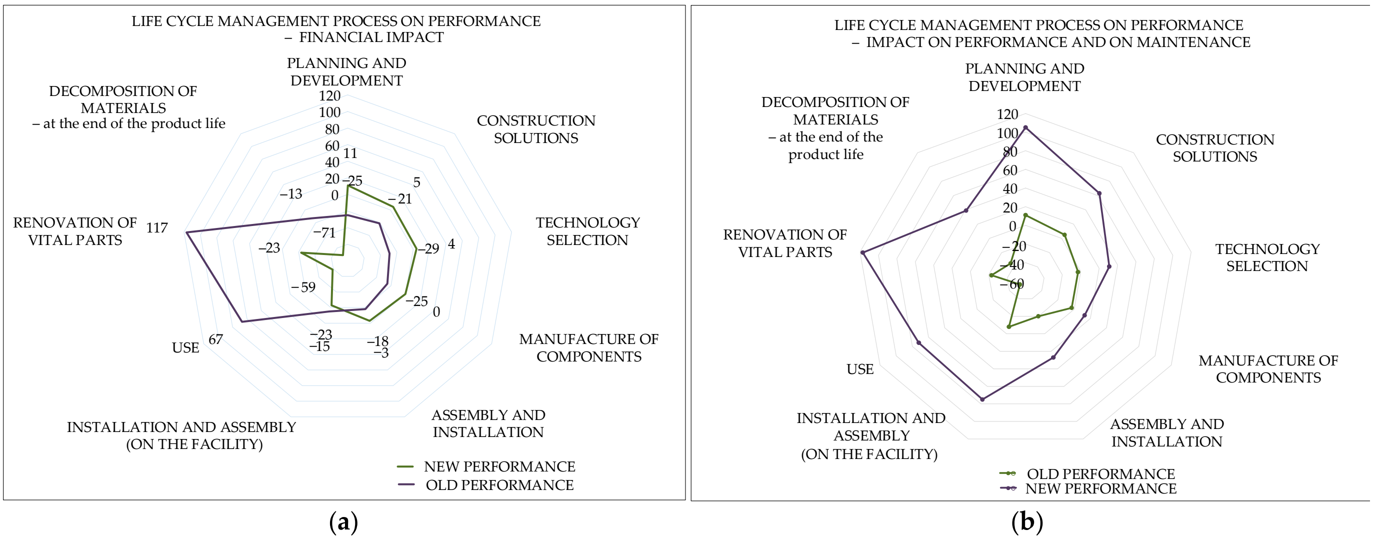


Figure 6. Sustainability impact of all changes to the runner: (**a**) financial impact, (**b**) impact on performance.

Other graphic presentations derived from the product life cycle management matrix or the house of sustainability for the Kaplan turbine runner (Figure 5) are shown in Appendix A.

Table 8 shows the results of the impact of changes for the user and the indicators of the sustainability impact of the new Kaplan turbine eco-runner.

Table 8. Assessment of the impacts of changes on the sustainability of the new Kaplan turbine eco-runner.

Assessment of the Impacts of Changes on the Sustainability Indicators of the New Eco-Runner	
Environmental impact	OLD VERSION: very negative impact (⇓⇓⇓⇓ 90%) very high likelihood of oil spillage from the runner into the environment due to a large number of seals and the operation itself use of nondegradable materials impregnated with oil and grease possibility of oil spillage into nature at each oil change and storage the oil must be changed or refined every year degradation necessary—costly processes once the degradation processes are completed, the oil poses a burden for the surroundings; usually this oil can also be used for heating—it returns to nature. oil storage (new and waste oil) special facilities are required in case of spillage ⇒ oil traps are required. it always poses an ecological risk (when in operation—spillage into the surroundings, when in storage—possible spillage into the surroundings) NEW VERSION: very positive impact (⇑⇑⇑⇑ 90%) use of new materials and the adjustment of the structure and sealing replacement of hydraulic oil with distilled water with viscosity-enhancing and lubrication additives
Impact on the use of materials	OLD VERSION: negative impact (⇓ 10%) no difference in use materials are impregnated with oil and grease NEW VERSION: positive impact (⇑25%) materials are not impregnated with oil and grease due to the use of new materials and the adjustment of sealing still in the testing and impact study phase
Impact on health	OLD VERSION: does not change—partial negative impact (⇓⇓ 50%) oil remains in all turbine components that are immersed in the hydraulic oil materials are impregnated with oil and grease NEW VERSION: does not change—partial positive impact (⇑⇑⇑ 75%) turbine components remain as they were installed still in the testing and impact study phase
Impact on safety	OLD VERSION: negative impact (⇓⇓⇓ 75%) hydraulic oil is flammable (high possibility of spillage during installation) the oil must be changed or refined every year decomposition is needed—in decomposition, burning substances remain in the air, water, and soil, which can have a very negative impact on living and, in the long run, on food production for people and animals. possibility of discharging oil into water and soil is always a potential killer of animals and life oil storage needed (for new and waste oils) special facilities are required in case of spillage ⇒ oil traps are required. it always poses an ecological risk (when in operation—spillage into the surroundings, when in storage—spillage into the surroundings) NEW VERSION: positive impact (⇑⇑⇑ 75%) distilled water with viscosity-enhancing and lubrication additives is not flammable no storage and no storing facilities needed in the case of spillage of distilled water into the environment, this poses almost no safety risk
Use for a customer—user	OLD VERSION: very negative impact (⇓⇓⇓⇓ 90%) very expensive (it is an expense for the end user) materials are impregnated with oil and grease hydraulic oil must be refined or replaced at least once a year and always poses an ecological risk special facilities for storage needed ⇒ special storage processes needed, oil traps are needed. it always poses an ecological risk (when in operation—spillage into the surroundings, when in storage—into the surroundings) NEW VERSION: very positive impact (⇑⇑⇑⇑ 90%) use of distilled water with viscosity-enhancing and lubrication additives no purchase and maintenance cost (no purchase and no storage due to the use of distilled water with additives) it does not pose an ecological risk no storage or replacement

Table 8. *Cont.*

Assessment of the Impacts of Changes on the Sustainability Indicators of the New Eco-Runner	
Material degradation—use for customer	OLD VERSION: very negative impact (⇓⇓⇓⇓ 90%) hydraulic oil is toxic, nondegradable, poses a burden for the environment degradation necessary—costly processes (once the degradation processes are completed, the oil remains a burden for the surroundings, which is a risk for the user) oil storage needed (for new and waste oils) an ecological problem remains NEW VERSION: very positive impact (⇑⇑⇑⇑ 90%) use of distilled water with viscosity-enhancing and lubrication additives no decomposition needed, no storage, no costs

As evident from Table 8, the most important impact in terms of the sustainability of the turbine runner is the environmental impact because it is as high as 90% both in the old (very negative) and in the new versions (very positive). For other indicators, the impact is, on average, 10%.

Of course, it is also worth mentioning the many constraints the team faced in implementing and executing sustainable solutions for the product—in our case, the Kaplan turbine. Kaplan turbines consist of key systems such as controls, lubrication system, servomotors, bearings, runner, and guide vanes; they can only function as a whole.

The customer's wish, and at the same time, the way to the most sustainable product, was to replace the hydraulic oil with a more environmentally friendly lubricating fluid or eco-Kaplan turbine.

After reviewing all systems and the possibility of changing the lubricating oil, it was found that such a solution was only possible for the runner, which accounts for only 18% of the total hydraulic oil consumption. However, the implementation of the eco-runner also encountered several limitations, such as:

- the design of the runner had to remain the same to work, so only new materials and technologies were chosen, i.e., the sealing and the use of a different lubricating fluid.
- the technology was changed without knowing how the new materials would react to the changed design and how the material would behave during processing,
- the choice of suitable new technology for the manufacture of components where no 100% guarantee of functionality could be given, due to ignorance of the material behavior (whether cast, forged, apprentice material, choice of corrosion protection—other types of protection are more suitable).
- problems caused by not knowing the durability of design parts—a series of tests were required (most realistic when tested in actual service).
- the use of a different seal, for which there was no 100% functional guarantee for the niche.
- the lack of adequate knowledge and technology to ensure testing of all factors affecting implementation reliability, and the lack of time and money for research and further testing were major constraints.

To this end, a proposal was made to all key stakeholders to install a smaller eco-Kaplan turbine for testing and new research purposes (to compare behavior during operation, ageing, or completion). Finally, the real results about the behavior of the turbine or the eco-runner can only be obtained by observing the behavior during actual operation.

When considering the possibilities for sustainable improvement of Kaplan turbines, only "possible" solutions have been proposed for all other systems, as there are currently no suitable solutions or technologies to ensure the functionality of operation and adequate implementation.

The potential possible solutions identified by the project team for other Kaplan turbine systems are shown in Table 9.

Table 9. Guidelines for possible solutions to other Kaplan water turbine systems.

	Possible Solutions to Other Kaplan Turbine Systems
Regulation system	Use of a lubricating fluid (other than oil) that is organic and has appropriate viscosity Robust structure to prevent spillage of lubricating fluid Double or triple sealing to prevent spillage of lubricating fluid Prevent oil leakage between base material and seals. Improved structure with better sealing properties, the seals should be more durable with a longer service life Strict inspections of the material for porosity (higher risk in castings, better suited are forgings or sheet metal) Improved pipe joints by choosing the most reliable joining technology (welding, soldering, joining materials, and regular maintenance and inspection)
Lubrication system	Use of a lubricating fluid (other than oil) that is more organic and has a lower environmental im-pact
Servo motors	System (air–oil) System (oil–water) System (air–water), which may be the best solution Distilled water operation (like in the runner). Accordingly, the following could be used: different seals and different materials (depending on the sliding properties), different sliding different machining due to viscosity (low tolerances can be achieved with oil) viscosity-enhancing additives that are not harmful to the environment and nonaggressive to the material, which affects the period until the restoration of parts) Testing of new materials, seals, and working fluid in the laboratory
Bearings	Water/fluid that prevents the shaft from fluctuating above the allowable threshold (when the run-ner is fastened and unevenly loaded, the bearings hold the shaft in the axis)

In general, the concept of sustainable development methodology addresses the fundamental determinants of sustainability, including availability, adaptability, and flexibility, which can be analyzed from a systems perspective. It is an environmental stewardship framework and therefore emphasizes, on the one hand, the development of systems that do not diminish, disrupt, or destroy ecological resources, places, and processes; on the other hand, it is an environmental stewardship framework because the fundamental cause of our ecological challenges is that our capacity to consume resources and disrupt ecological systems far exceeds their regenerative and restorative capabilities. More generally, the sustainability of any system can be represented by a valuation function of the system's outputs of interest under consideration. We can have different perspectives in the context of the criteria of very strong, strong, weak and very weak sustainability. General standards need to be specified in specific systems, such as: What needs to be sustained (in this specific system)? At what level and in what way? How should it be measured and monitored?

Therefore, the general criteria for different types of systems or activities are proposed, such as:

- sustainable production does not release toxins into the environment,
- sustainable energy production does not depend on increasingly scarce natural resources or cause significant climatic changes,
- sustainable development does not endanger living conditions.

Sustainability is composed of three pillars: economy, society, and environment. The strengths of "sustainability" as a concept for environmental protection are that it addresses the root cause of environmental problems in general and can be applied to almost any type of system or activity. The differences in sustainable implementation of different methods or products are related to the implementation options and the different constraints associated with the functionality of the product or system and the implementation options, such as limitations of the existing technology, material properties, and other constraints. There are many limitations and constraints that make it impossible to apply a sustainable product development model to many products and different systems that should be considered:

- Environmental limits:
    (1) Environmental limits do not exist or are considered automatically self-limiting.

(2) Natural resources are finite, and the capacity of ecosystem is limited.

- Limits in technology, science, and research: Not all emerging technologies consider the concept of sustainability, and no technology (even clean energy technologies) is fully sustainable.
- Social awareness: Especially in developing countries, awareness of the importance of supporting sustainable solutions is low.
- economic limitations:

(1) Source limits (scarcity of natural resources) and sink limits (saturation of natural capacity to dilute and neutralize pollutants and wastes).

(2) Policy directives [3,4] impose many economic limits on both developed and developing countries for the proposed different sustainable solutions, which however usually do not lead to economic growth and financial gain. This is also the main reason why these policies are not applied, because in economics only the big profit is necessary.

- Public policies are not ready to support environmental, social, and (or) economic sustainability.

6. Conclusions

This paper illustrates the implementation of a concurrent product development project, wherein the product development had to be extended with sustainable development elements. We have learned from literature and experience on new product development projects that product properties can be most influenced upon in the early stages of development, i.e., in the product design and construction phase.

Currently, when developing a product, it is important that it is realized in the shortest possible time, with the lowest possible costs and in the required quality [33]. This can be achieved by extending the classic project management with concurrent engineering strategies based on the track-and-loop principle. In this way, individual phases of product development take place concurrently in the concurrent engineering loops. Each loop is under the responsibility of the working team who plans and manages the work in carrying out the activities in the loop. When the goals of the observed loop are achieved, the activities progress to the next loop and the planning and management work in the loop is taken over by the next working team, which is usually only a partially modified team of the previous loop, so continuity is maintained. Due to constant mutual cooperation, the exchange of information, and the use of agile project management methods within a loop, possible errors that would cause problems in the subsequent product development stages and therefore increase the cost of product development are eliminated.

From the point of view of product sustainability, it is important that the goals are set at the initial stage and that all further procedures and solutions to the product are subordinated to the achievement of these goals. Among the concurrent engineering tools, the QFD method is important. It can be used to transform input requirements (called the voice of the customer) into development strategies for or technical solutions to the product. If we want the product to meet the sustainability requirements, the QFD must primarily include the requirements relating to the expected product sustainability. Development strategies or technical solutions must be assessed primarily in terms of feasibility and, of course, in terms of financial impact. To this end, the classic QFD was transformed into an integrated product lifecycle management matrix, or, in short, the house of sustainability. The classic approach in assessing the degree of correlation between input requirements and strategies was preserved in that a sign from the correlations was added, namely whether a certain solution has a positive or negative impact on product properties.

The proposed methodology of concurrent product development and the house of sustainability were illustrated on the example of a development of a new Kaplan turbine for a hydroelectric power plant. This project led us to a conclusion that feasible possibilities for achieving product sustainability are attainable only by performing changes to the runner. Having studied various structural solutions, selection of new materials and technologies, we found that the coolant of the existing runner can be replaced with distilled water, to which viscosity-enhancing and lubrication additives are added. A detailed analysis has revealed that this change does not significantly affect the operation of the turbine itself, but it has a huge impact on environmental and social factors. It is important that, in addition to the above factors, positive financial impacts are observed, not only in the production itself but in operation and finally decomposition.

In implementing sustainable development and sustainable product development, several factors affect performance differently, namely management support, teamwork, and quality tools and systems.

Management has the most significant role and at the same time the greatest influence with its strategy and management policy, which includes the awareness of all people involved in the process of sustainable product development.

For management, full support in practice means:

- the provision of sufficient financial resources and time, as well as the training of employees,
- active participation in the definition of strategic goals,
- taking the suggestions of the employees involved seriously.

The second crucial influencing factor is good teamwork in each loop of sustainable product development and effective and clear communication about the goals. Communication and sharing of ideas within teams and across relevant functions of an organization are key to success. Communication and interaction as part of employee engagement ensure a focus on tangible improvements and bring ideas about a product's sustainability to fruition.

A third important influencing factor is the use of methods and tools. Sustainable development can begin by analyzing environmental impact throughout the life cycle using life cycle assessment (LCA). Using this method provides information on which stages of the product life cycle are most important. With this information, we can prioritize and focus on the relevant phases of the life cycle. However, the use of tools is not a prerequisite for implementing sustainable product development. Sustainable product development is a dynamic process so we can start with small goals. A good start is to move forward, step by step, and focus on concrete ways to reduce environmental impact as part of this iterative process.

An experiment of applying the proposed process of simultaneous development of a sustainable product was conducted on a product where the sustainability requirements are relatively easy to determine. However, the general applicability of the proposed methodology requires further research. Furthermore, the research presented has additional limitations. First and foremost, since this is a pilot project, we encountered a lack of knowledge in the area of selecting and using new, more environmentally friendly materials. The second limitation concerns the behavior of the new solutions during the use of the product, as the product in question is expected to have a lifetime of more than 40 years.

Further research will be focused on other turbine systems, as only 18% of the total amount of oil is in the runner. Of course, the use of water in other systems will have to be subject to preliminary research. Then, the house of sustainability will have to be used to check the effects of the proposed solutions in terms of all aspects of sustainability. The second set of research will focus on the further development of the house of sustainability to the level of production processes.

Author Contributions: Conceptualization, J.K. and L.R.; methodology, J.K.; validation, L.R., formal analysis, L.R.; investigation, J.K. and L.R.; resources, L.R.; data curation, L.R.; writing—original draft preparation, J.K.; writing—review and editing, J.K and L.R.; visualization, L.R.; supervision, J.K.; project administration, L.R.; funding acquisition, J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was partially supported by the Ministry of Higher Education, Science and Technology of the Republic of Slovenia, grant number 1000-15-0510, and by the Slovenian Research Agency, grant number P2-0270.

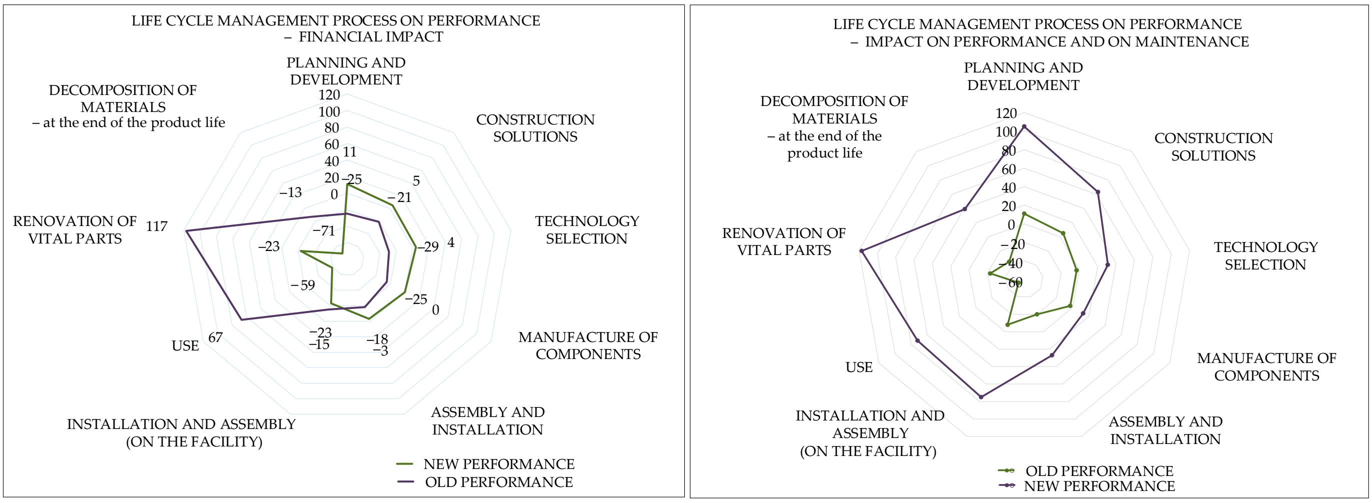
Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study is available upon request from the corresponding author. The data is not publicly available due to business secrecy.

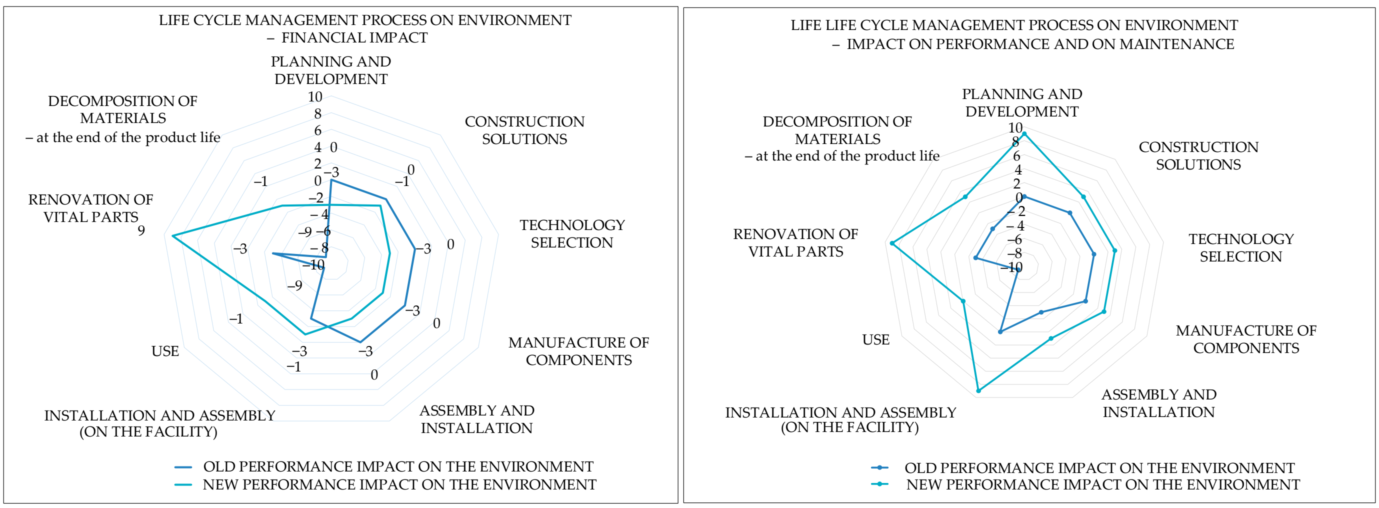
Conflicts of Interest: The authors declare no conflict of interest.

Appendix A



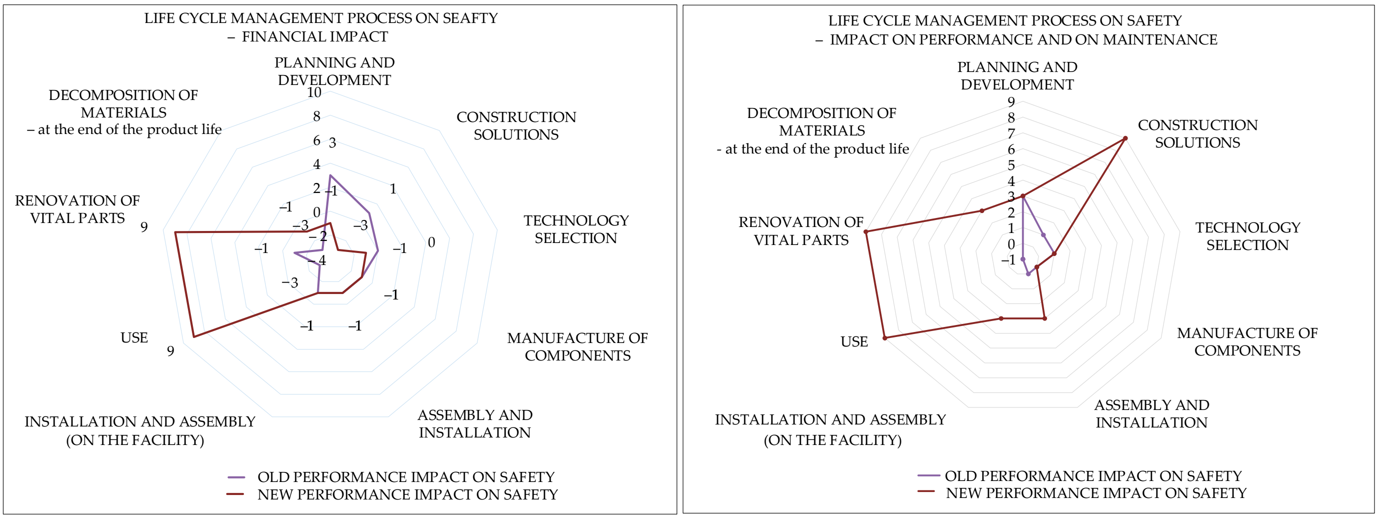
(a) (b)

Figure A1. Impact of new materials on the runner sustainability: (**a**) financial impact, (**b**) impact on performance.



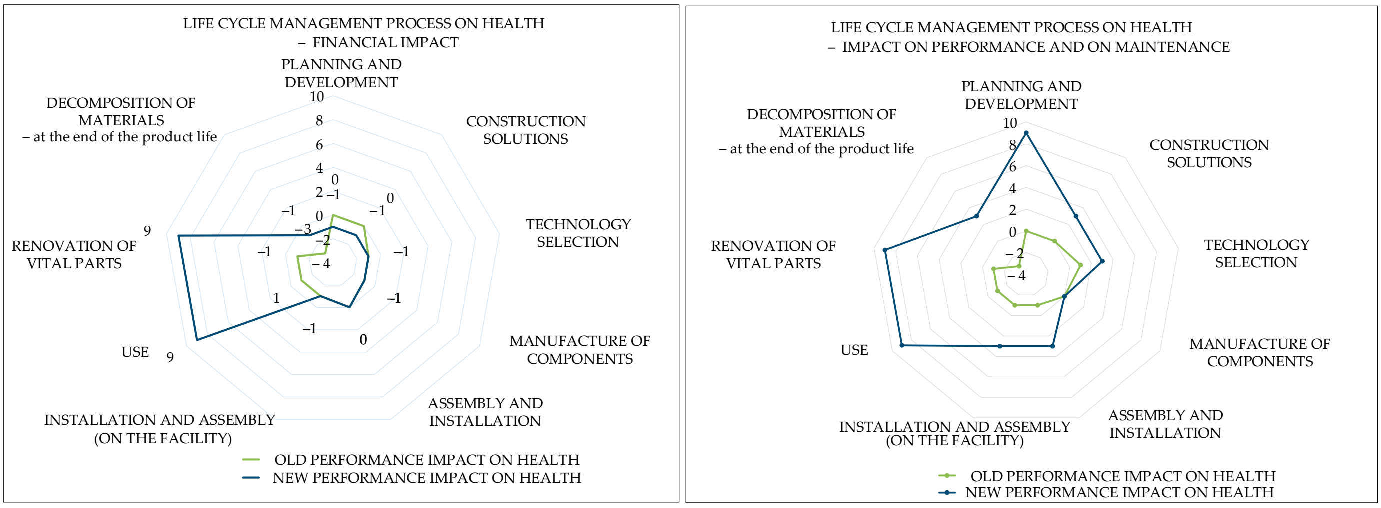
(a) (b)

Figure A2. Sustainability-related impact of the runner on the environment: (**a**) financial impact, (**b**) impact on performance.



(**a**) (**b**)

Figure A3. Sustainability-related impact of the runner on safety: (**a**) financial impact, (**b**) impact on performance.



(**a**) (**b**)

Figure A4. Sustainability-related impact of the runner on health: (**a**) financial impact, (**b**) impact on performance.

References

1. Rosen, M.A.; Kishawy, H.A. Sustainable Manufacturing and Design: Concepts, Practices and Needs. *Sustainability* **2012**, *4*, 154–174. [CrossRef]
2. Gupta, S.; Dangayach, G.S.; Singh, A.K. Key Determinants of Sustainable Product Design and Manufacturing. *Procedia CIRP* **2015**, *26*, 99–102. [CrossRef]
3. UN Resolution of the General Assembly A/RES/70/1: Transforming our world: The 2030 Agenda for Sustainable Development 2015. Available online: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf (accessed on 13 November 2020).
4. Communication from the Commission to the European Parliament, The Council, The European Economic and Social Committee and The Committee of the Regions, Next Steps for a Sustainable European Future European Action for Sustainability. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52016DC0739&from=EN (accessed on 13 November 2020).
5. Development strategy of Slovenia to 2030. Available online: https://www.gov.si/assets/vladne-sluzbe/SVRK/Strategija-razvoja-Slovenije-2030/Strategija_razvoja_Slovenije_2030.pdf (accessed on 13 November 2020).
6. Glišović, S. Environmental life cycle management as a framework for successful project development. In Proceedings of the 13th International Conference on Management and Safety, Ohrid, Macedonia, 15–16 June 2018; Taradi, J., Ed.; The European Society of Safety Engineers: Čakovec, Croatia, 2018.

7. Hapuwatte, B.M.; Jawahir, I.S. A total life cycle approach for developing predictive design methodologies to optimise product performance. *Procedia Manuf.* **2019**, *33*, 11–18. [CrossRef]
8. Rihar, L.; Žužek, T.; Kušar, J. How to successfully introduce concurrent engineering into new product development? *Concurr. Eng.* **2020**. [CrossRef]
9. Lin, Y.; Cheng, H.-P.; Tseng, M.-L.; Tsai, J.C.C. Using QFD and ANP to analyse the environmental production requirements in linguistic preferences. *Expert Syst. Appl.* **2010**, *37*, 2186–2196. [CrossRef]
10. Lam, J.S.L.; Lai, K. Developing environmental sustainability by ANP-QFD approach: The case of shipping operations. *J. Clean. Prod.* **2015**, *105*, 275–284. [CrossRef]
11. Hsu, C.-H.; Chang, A.-Y.; Luo, W. Identifying key performance factors for sustainability development of SMEs—Integrating QFD and fuzzy MADM methods. *J. Clean. Prod.* **2017**, *161*, 629–645. [CrossRef]
12. Yazdani, M.; Chatterjee, P.; Zavadskas, E.K.; Hashemkhani Zolfani, S. Integrated QFD-MCDM framework for green supplier selection. *J. Clean. Prod.* **2017**, *142*, 3728–3740. [CrossRef]
13. Onat, N.; Bayar, H. The sustainability indicators of power production systems. *Renew. Sustain. Energy Rev.* **2010**, *14*, 3108–3115. [CrossRef]
14. Klein, S.J.W.; Whalley, S. Comparing the sustainability of U.S. electricity options through multi-criteria decision analysis. *Energy Policy* **2015**, *79*, 127–149. [CrossRef]
15. Kaebernick, H.; Kara, S.; Sun, M. Sustainable product development and manufacturing by considering environmental requirements. *Robot. Comput. Integr. Manuf.* **2003**, *19*, 461–468. [CrossRef]
16. Otero, M.; Pastor, A.; Portela, J.M.; Viguera, J.L.; Huert, M. Methods of Analysis for a Sustainable Production System. In *Climate Change—Research and Technology for Adaptation and Mitigation*; Blanco, J., Kheradmand, H., Eds.; IntechOpen: Rijeka, Croatia, 2011.
17. Lee, K.-M. Sustainable Products and Sustainable Production: Introduction. In *Handbook of Sustainable Engineering*; Kauffman, J., Lee, K.-M., Eds.; Springer: Dordrecht, The Netherlands, 2013; pp. 261–267. ISBN 9781402089398.
18. Dai, J.; Blackhurst, J. A four-phase AHP–QFD approach for supplier assessment: A sustainability perspective. *Int. J. Prod. Res.* **2012**, *50*, 5474–5490. [CrossRef]
19. Madzík, P.; Lysá, L'.; Budaj, P. Determining the Importance of Customer Requirements in QFD—A New Approach based on Kano Model and its Comparison with Other Methods. *Q. Access Success* **2019**, *20*, 3–15.
20. Singh, A.K.; Rawani, A.M. Improving the weight of Technical Attributes in Quality Function Deployment by the Integration of Techniques for Order of Preference by Similarity to Ideal Solution method. *Int. J. Prod. Perform. Manag.* **2020**. [CrossRef]
21. Zimon, D.; Madzik, P.; Sroufe, R. Management systems and improving supply chain processes: Perspectives of focal companies and logistics service providers. *Int. J. Retail Distrib. Manag.* **2020**, *48*, 939–961. [CrossRef]
22. Zimon, D.; Madzik, P.; Sroufe, R. The Influence of ISO 9001 & ISO 14001 on Sustainable Supply Chain Management in the Textile Industry. *Sustainability* **2020**, *12*, 4282.
23. Lindow, K.; Woll, R.; Stark, R. Developing Sustainable Products: An Interdisciplinary Challenge. In *ICoRD'13. Lecture Notes in Mechanical Engineering*; Chakrabarti, A., Prakash, R., Eds.; Springer: New Delhi, India, 2013. [CrossRef]
24. Masui, K. Environmental Quality Function Deployment for Sustainable Products. In *Handbook of Sustainable Engineering*; Kauffman, J., Lee, K.M., Eds.; Springer: Dordrecht, The Netherlands, 2013. [CrossRef]
25. Rahimi, M.; Weidner, M. Integrating Design for Environment (DfE) Impact Matrix into Quality Function Deployment (QFD) Process. *J. Sustain. Prod. Design* **2002**, *2*, 29–41. [CrossRef]
26. Masui, K.; Sakao, T.; Kobayashi, M.; Inaba, A. Applying Quality Function Deployment to environmentally conscious design. *Int. J. Q. Reliab. Manag.* **2003**, *20*, 90–106. [CrossRef]
27. Rihar, L.; Kušar, J.; Duhovnik, J.; Starbek, M. Teamwork as a Precondition for Simultaneous Product Realisation. *Concurr. Eng.* **2010**, *18*, 261–273. [CrossRef]
28. Winner, R.I.; Pennell, J.P.; Bertrand, H.E.; Slusarczuk, M.M.G. *The Role of Concurrent Engineering in Weapons System Acquisition*; IDA Report R-338; Institute for Defense Analysis: Alexandria, VA, USA, 1988.
29. Rihar, L. Generalized Model of Concurrent Product and Process Development. Ph.D. Thesis, University of Ljubljana, Ljubljana, Slovenia, 2014.
30. Janekova, J.; Fabianova, J.; Fabian, M. Assessment of economic efficiency and risk of the project using simulation. *Int. J. Simul. Model.* **2019**, *18*, 242–253. [CrossRef]
31. Prester, J.; Buchmeister, B.; Palčič, I. Effects of advanced manufacturing technologies on manufacturing company performance. *SV-JME* **2018**, *64*, 763–771. [CrossRef]
32. Strmčnik, E.; Majdič, F.; Kalin, M. Water-lubricated behaviour of AISI 440C stainless steel and a DLC coating for an orbital hydraulic motor application. *Tribol. Int.* **2019**, *131*, 128–136. [CrossRef]
33. Sremcev, N.; Stevanov, B.; Lazarevic, M.; Mandic, J.; Tesic, Z.; Kuzmanovic, B. Improving process of quotation creation through value stream mapping and simulation. *Int. J. Simul. Model.* **2019**, *18*, 563–573. [CrossRef]