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# Offering Carbon Smart Options through Product Development to Meet Customer Expectations

**Diana Blagu, Denisa Szabo, Diana Dragomir *, Călin Neamțu and Daniela Popescu**

Department of Design Engineering and Robotics, Technical University of Cluj-Napoca, 400114 Cluj-Napoca, Romania
* Correspondence: diana.dragomir@muri.utcluj.ro

**Abstract:** Addressing the global threat of climate change is one of the present priorities of both companies and their customers. Societal trends demand a significant change in consumer behavior in the foreseeable future to contribute to the reduction in carbon emissions reaching the atmosphere, and national and international governments are committing their resources and efforts to this complex endeavor. The current paper addresses the other side of this conundrum, which is how firms can propose carbon-smart alternatives for their products on the market, in order to match the growing interest and the changing behaviors of the consumers. For this purpose, a research and innovation methodology is proposed to expand the design for concept X, namely, the design for sustainability set of guidelines in the area of developing products with a reduced carbon footprint under conditions of timeliness and economic viability. The research is based on refining practical experience and the use of consecrated management techniques and is validated through the employment of a Delphi-based forecasting process. The authors conclude that the large-scale adoption of such recommendations for the various domains of the manufacturing sector has the potential to contribute to climate change mitigation significantly.

**Keywords:** low-carbon economy; new product development; consumer behavior

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## 1. Introduction

Considered a planetary level threat, climate change has the potential to affect and fundamentally change the way society lives and economy supports it. There are no easy answers to this complex issue, and it is becoming increasingly clear that a concentrated effort of all nations, companies and consumers is required to generate results within the international frameworks established by the United Nations and its systems of treaties. The European Union is a global leader in this direction and its member countries are undertaking difficult transformations to conform to a low-carbon future, which has the potential to limit the negative effects of climate change.

The relationship between intentions and possibilities sits at the center of developing and reinforcing pro-environmental behavior in consumers. Since becoming environmentally conscious and upholding products with a reduced carbon footprint is a novel requirement, regular buyers of consumer products need support and options that are easy to adopt and have a measurable impact. On the other hand, companies are still developing their capabilities in this field and could benefit from mature, research-based solutions. Following previous research [1], in which we attempted to figure out the ongoing status of manufacturing companies in the Transylvanian region, the current paper presents an aide for them to develop new products in a sustainable manner. A dedicated methodology has the capability to integrate and showcase existing approaches and to support the development of new and improved ones. Besides new materials and new technologies, we believe that the product development process itself can contribute to establishing a flourishing market that would benefit the climate.

Hence, the purpose of this research is to develop a model which guides design engineers to develop new products in a more sustainable way. The model proposed contains 30 principles adapted to each stage the product would follow from the beginning to the end of its life, detailing the design for sustainability approach. The principles developed focus on reducing the carbon footprint of the new products, contributing to meeting customer expectations in an environmentally friendly way.

## 2. Materials and Methods

The methodology applied was intended to transform product development and design experience into useable guidelines to be applied within a design for sustainability (DfS) approach by companies in the manufacturing industry. For this purpose, a three-stage approach is presented in Figure 1 and described in the following section.

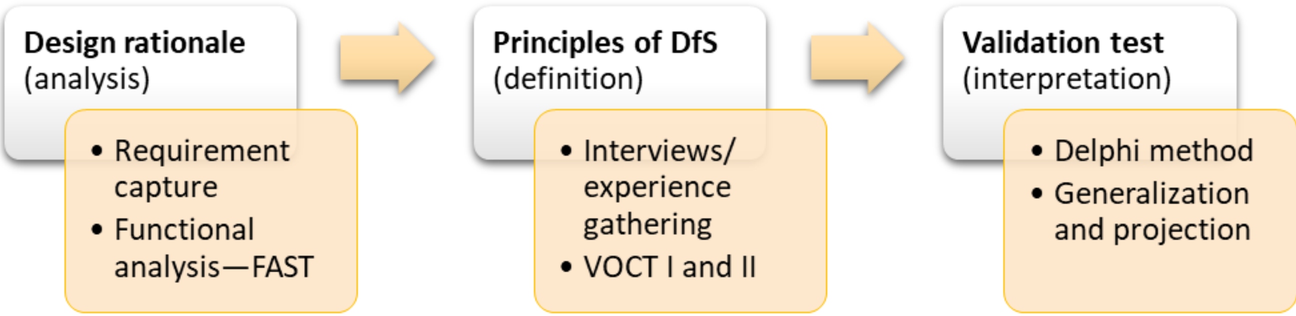


**Figure 1.** Research and innovation methodology to identify and consolidate DfS principles (own research).

The first stage focused on determining and analyzing the design rationale behind the current product development approaches. For this purpose, a requirement capture process was completed, including a current literature study and a functional analysis of representative manufactured products. The latter activity was implemented using the functional analysis system technique (FAST) deployed with the help of yEd diagramming software and was centered upon uncovering the core decisions taken during the product design process. By performing these tasks, the authors ensured that a clear and comprehensive model was used as the basis for studying the improvement mechanisms necessary in approaching the environmental objectives that were being asked, with increasing interest by the society at large.

In the second stage, our team performed a qualitative assessment of the previously identified elements using 14 interviews conducted with design experts from manufacturing companies in Romania, selected on the basis of their market success from four advanced industries, and then refining this know-how. Additionally, using Qualica QFD, a tool named the Voice of the Customer (Tables I and II) was used to support the definition of new principles for the design for sustainability approach geared towards reducing the carbon footprint during the product's life cycle. A comprehensive list of 30 proposals was created, taking into account practical, regulatory, and conceptual considerations, in an integrative demarche. This list included aspects related to the way companies processed requirements, how they collaborated with suppliers, what they conducted within their facilities and how they related to external scrutiny. In this context, the proposals covered the main objectives of the product development process, in order to secure as much carbon emission reduction as possible.

In the third and final stage of the methodology, the upgrade and validation of previous proposals was realized by means of a Delphi forecasting process and a generalization step. The first part was implemented with the support of the Welphi [2] software-as-a-service tool, and it involved two rounds of feedback from experts (14 persons in the first sequence and 10 in the second) in product development and product manufacturing in high tech—high-quality fields such as automotive, aerospace, machinery, electrical and electronics. They performed different roles within their organizations; eight of them were design expert engineers and six of them were manufacturing expert engineers. In terms of their field of activity, three of them came from academia, three from the automotive sector, five from electrical and electronic equipment companies, two from machinery and one from aerospace. Reflecting this diversity, the principles validated in round 2 added significant weight in terms of their applicability to industry.

The resulting form of the 30 principles for low-carbon design of products was then interpreted and projected for all areas of the manufacture. At the same time, some of the experience gained in the implementation of this procedure could be transposed in other sectors as well, e.g., services, agro-food industry, tourism, energy, etc.

The authors believe that by applying a systematic methodology that makes use of consecrated management tools and dedicated software capabilities, the results obtained would have a high degree of certainty and reproducibility in other similar situations. Furthermore, the possible impact in terms of competitiveness becomes easier to measure and compare across domains.

## 3. State-of-the-Art and Requirement Identification

When developing new products for current markets and customers, the companies of today must observe the relationship that new generations have established with the environment and their preoccupations for protecting nature and limiting climate change. Scientific articles that study the approaches and mechanisms employed by firms when performing this task arrived at the conclusion: that structured and mature project management and product development processes can leverage the transition to design for sustainability across industries [3]. Within this trend, dedicated and mathematically viable capturing and processing requirements can be conducted to support product development with respect to low-carbon economy goals [4]. This is especially needed in the traditional manufacturing industry that does not place a high emphasis on environmental requirements for which carbon quantification is obfuscated and complex [5]. Within this context, and factoring in the current experience in new product development (NPD) of authors and their industrial partners, we could surmise that product innovation [3], product quality planning [6] and the quality management system [7] of companies involved in such endeavors must be considered mandatory parts of the design rationale and design decisions to be determined in preparation for sustainability and low-carbon-related challenges.

Customization is presently one of the driving forces of competitiveness, which makes it difficult to correctly assess the environmental impact of products and processes in a holistic manner. The design of a specific product depends on the correct design of the process and its tools (the other way around too), thus, the transformations to natural factors must be understood in both directions [8]. A number of authors [9,10] theorized that problems with the design of current low-carbon products also stem from the lack of dedicated procedures and tools, even if proposals are continually discussed based on algorithms such as TRIZ [10]. If presented with the option to use a new or used product, the clients are usually faced with a dilemma related to the active or useful life of the artefact, but for the products to be remanufactured and still be attractive, an important role belongs to the integration of carbon taxes in the production cost, as policy instruments that can be changed by representatives of a community or society [11]. The carbon footprint and its management should also be addressed in conjunction with the average lifetime costs of products, as components (e.g., in the case of a smartphone) may be replaced in order to boost functionality and reduce the carbon footprint, without forcing the creation of a new product iteration [12]. In order to allow for the merging of competitiveness and sustainability goals in product development, a clear definition of design principles is needed, such as the one discussed by [13], which is based on the DFMA (design for manufacture and assembly) approach. For our endeavor, the previous literature review section revealed the following requirements to be addressed by product designers seeking to meet customer behavioral expectations: the perceived impact of functions for both the users and the developers, and the life cycle related requirements that create a complex network of possibilities.

Anthropic activity is the main source of carbon emissions, and public awareness of this is growing, leading to changes in buying and use behavioral patterns, encouraging the developers and manufacturers of products to find new solutions for creating products that customers are interested in [14]. Customers are not content anymore with just receiving products, and, in many cases, they seek to influence development, such as with the concept of customer collaborative product innovation, which ensures the requirements are integrated into the manufacturers' processes and products from the earliest possible moment [15]. Other authors present the way in which such solutions for reducing greenhouse gas emissions for a given product can then be generalized to the design of product families or even beyond, to the level of supply chains or industries [16,17]. Of course, out of all determinants, the transition to a low-carbon economy can be enabled mostly by the advent of new materials that must subscribe to the concept of circularity and use the growing resources of bioeconomy and biotechnologies [18]. Still, bringing these from the laboratory to the manufacturing floor, especially in metal processing industries where substitution if difficult, is a complex engineering challenge. The decarbonization of a new product development process must also be cost sensitive in order to succeed in the long run, and this process is a taxing one, often times requiring trial and error [19]. For our further detailed analysis, we retained requirements related to the cost–benefit perceived balance, materials and supply chains.

Another set of compelling requirements to be treated comes from the relation of the structured product lifecycle management and the manufacturing process used to generate it. For instance, the plastics industry is a vital component of consumer and household goods production and its continuous effort at recyclability and circularity is currently being expanded by the large-scale use of biodegradable polymers, also contributing to reducing carbon dioxide emissions [20]. Similarly, in the wood processing industry, the carbon footprint of the mass production of furniture and other forest-based products creates a considerable demand for new processing technologies and new manufacturing equipment, adequate for the current environmental and climate requirements [21]. This relation also extends to energy production (also useful for manufacturing companies), as biomass is a convenient and clean biofuel, which can be used in many situations instead of fossil fuels, but whose carbon footprint issues must be readily addressed [22].

The new product development process must deal with multiple objectives and technologies and, therefore, it is critical that it be informed by the contributions of research and development personnel, as it is not as intuitive as in previous eras of manufacturing. The need for modern and scientifically sound methods of product design is increasing, with classic approaches lacking instruments and mathematical models to address environmental impact and carbon footprints [23]. Additionally, the smart product paradigm is gaining ground and contributing to the way in which manufactured items interact with environmental factors by using sensor information and data processing. Conversely, access to the correct information for customers and company staff appears to facilitate carbon emission reduction and biodiversity preservation through enhanced behaviors and practices [24]. As a consequence, the last set of requirements to be added to the design rationale mapping includes, on the one hand, the connection between product design and *R&D* execution and, on the other hand, results and product extension by the use of information and smart features.

Based on the identified requirements, a functional analysis using FAST (functional analysis system technique) was realized (see Figure 2 above), to facilitate the brainstorming process required for the next step of the methodology.

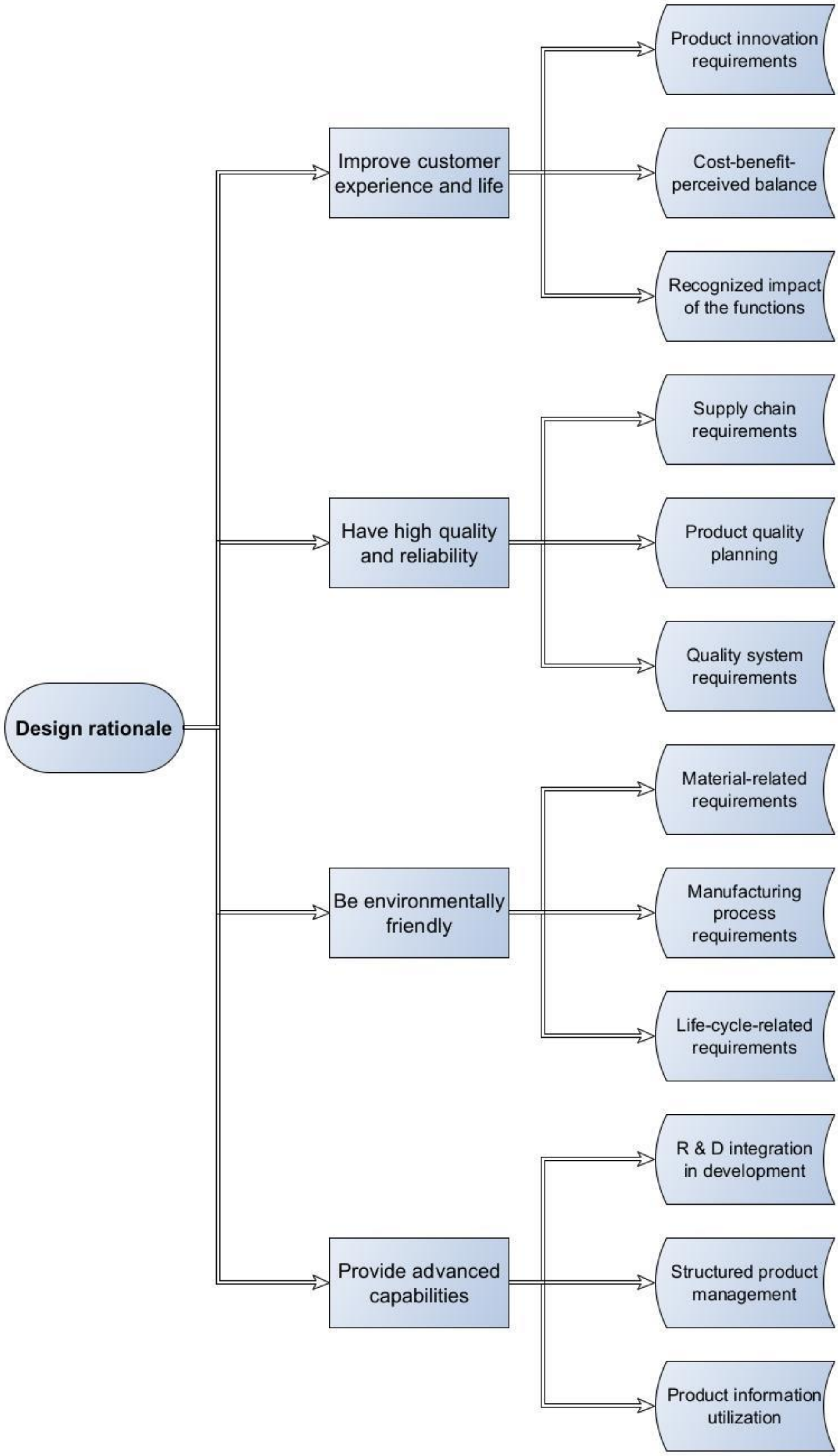


**Figure 2.** FAST functional analysis of representative manufacturing goods—function and requirement categories (own research).

## 4. Developing Principles for Design for Sustainability (DfS)

In the second stage of the implemented methodology, the research team employed the use of structured and unstructured interviews with over 14 representatives of manufacturing domains, such as plastic parts, furniture, metallic construction and other smaller domains represented in Romania, but also representative on a European scale. The purpose of these discussions was to gather the experience of engineers and managers from such companies, combine it with the team's own production and consulting experience and use it to transform the comprehensive requirements of the design rationale into workable principles for design for sustainability, with a focus on carbon emission reductions.

The processing phase of this stage involved the use of the Qualica QFD software and its dedicated templates for the Voice of the Customer, Tables I and II. As it can be seen in Figure 3 below, the first table performed a contextual 5W1H analysis to understand the conceptual mechanisms that compelled product designers to adopt a certain option, while the second table sought to identify key indicators for critical technical characteristics, the way in which product functions were delivered and the main possible failures, thus, facilitating the definition of the 30 DfS principles. Since this was laborious work and the presentation space was limited, we showcased in the figure the operations performed upon one of the rationale's elements that led to four principles (i.e., supply chain requirements).

| What? | Who? | When? | Where? | Why? | How? |
|---|---|---|---|---|---|
| What is really meant? Rephrased customer need for use in QFD | Who is requesting this? | When is the product being used? | Where is the product being used? | Why is this being requested? | How can it be done? |
| Good relations with suppliers | Customers | Product development | Within the company | Common environmental effort | Bilateral trust and co-construction |
| Environmental management systems | Users | Product design | With the users | Cost sharing | Industry associations (e.g. clusters, ecosystems) |
| Measuring and monitoring of CO2 | Authorities | Manufacturing | Intermediary locations | Market pressure | Environmental / climate legislation |
| | Interest groups | Distribution | Landfill | Operating conditions | |
| | | Use | | | |
| | | End of life | | | |

| Needs | CTQs | Functions | Reliability |
|---|---|---|---|
| Rephrased customer need for use in QFD | Related Critical to Quality Characteristics | Related product or service functions | Related potential faults |
| Good relations with suppliers | Common product development projects | Environmental impact | Product is not environmentally competitive |
| Environmental management systems | Litigations with suppliers | End of life options | Product suffers failures with environmental impact |
| Measuring and monitoring of CO2 | Profit sharing schemes | Servicing needs | Product is withdrawn from the market by the authorities |

**Figure 3.** VOCT I and II implemented with Qualica QFD to refine NPD requirements (own research).

By following this approach, the entire set of principles was derived from the identified components of the design rationale when product developers are focused on diminishing the environmental impact and reducing carbon emissions. These principles (see Table 1) are meant to act as a guide for companies to provide green alternatives on the market that customers can choose according to their environmentally conscious behavior, validating their belief and contributing to climate change mitigation.

**Table 1.** List of main requirements for representative manufactured goods.

| | |
|---|---|
| Organization ability to meet sustainability principles | Extending the product lifetime to maximum |
| Organization capacity to produce using renewable energy sources | Optimizing the amount of packaging required |
| Low-carbon materials needed to develop the product | Packaging materials should come from recycling or reuse activities |
| Products developed with a modular design | Packaging materials should have recycling or reuse properties |
| Optimizing the packaging solutions | Transport equipment should be low-carbon |
| Ensuring a high level of technological maturity | The product usage should have a minimal carbon footprint |
| Analyzing the carbon footprint of the product | Building products with smart features or low consumption |

**Table 1.** *Cont.*

| | |
|---|---|
| Choosing suppliers that have a small carbon footprint | Repair processes should have a minimal carbon footprint |
| Greater usage of standardized materials | Easy repair process of the product |
| Choosing to collaborate with companies that have a circular economy mindset | Attaching replaceable modules to the product |
| Recycling or reuse of process waste materials | Easily recycle or reuse the product or its components |
| Choosing production technologies with low environmental impact | Extending the life of products with additional support activities |
| Optimizing the workflow operations | Optimizing the usage of consumables |
| Providing a good stability, capability and maturity of processes | Developing channels for recycling and/or reusing the product at the end of its life |
| Calculate the carbon footprint of the companies' processes | Keeping the carbon footprint for recycling processes to a minimum |

## 5. Validation Testing Using the Delphi Method

The aim of this study was to propose and then validate a set of principles to underpin a low-carbon design approach based on the design for sustainability (DfS) model. The Delphi questionnaire was applied to validate the design for low-carbon model developed by the authors, and consisted of 30 principles developed according to the product life cycle and adequate methods for environmental issues.

The methodology of applying a Delphi survey consisted of two rounds, where the purpose of the first round was to collect the additional recommendations of the panel of experts for each principle, and the second round's purpose was to add the recommended improvements into the principles and send them back to the experts to validate them.

The principles, in both rounds of the Delphi survey, were defined according to the tables below, and almost every one of them had to be adjusted slightly. Therefore, for all tables below, the left side shows all principles from the first round and the right side shows the final principles validated in the second round of the Delphi survey. The validation of the principles was performed by comparing the scores obtained in both rounds. Scores were calculated by measuring the degree of agreement with all the principles developed using a five-level scale, where five means "strongly agree", four means "agree", three means "neither agree nor disagree", two means "disagree" and one means "strongly disagree", and then working out an average of all the responses obtained.

As can be seen in the following figures, all the scores for each principle could be seen in comparison with both rounds that took place in the Delphi questionnaire. Additionally, the orange bars indicate the scores reached for the principles in the first round and the blue bars signify the scores reached in the second round.

In addition, for the first round, almost all the scores obtained were above four, which meant that they were validated by the panel from the first round. There were only a few principles where the score was less than 4, but still higher than 3.5, which reflected a good overall vision for all defined principles. The average of all scores obtained in the first round for all principles was 4.23, which meant a good to very good degree of acceptability was achieved. Additionally, in the second round, we tried to integrate all recommendations to increase the level of acceptability, especially for those with lower scores. The average score obtained in round two for all principles was 4.62, a substantial increase over the first round by 0.39.

Furthermore, if respondents' opinions on the principles were less than or equal to "neither agree nor disagree", they were required to add a comment explaining why the defined principle was not good enough and how it could be improved. In addition, the recommendations received for each principle were fed into the second Delphi round, and both versions are presented below, along with the shortcomings of the first round.

The principles were defined according to the life cycle model of a product. Therefore, for the first stage of the life cycle, customer needs and requirements, the first two principles shown in Figure 4 were drawn. As can be seen, the blue bars for both principles were higher compared to the orange bars, which represented that, in the second round, the panel's level of confidence in the low-carbon principles developed increased.

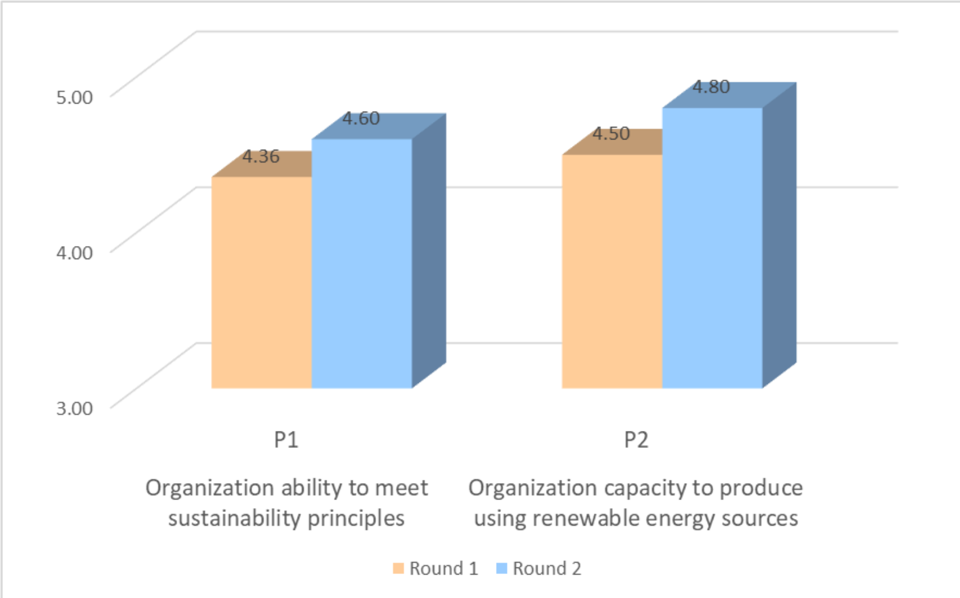


**Figure 4.** Principles defined for the needs and requirements phase (own research).

In Table 2, the P1 and P2 principles required to achieve a low-carbon product from the first stage of its life cycle are presented. Hence, when a decision is determined to develop a new product and when customer needs and requirements are identified on the market, organizations should also look for their ability to meet sustainability principles and their capacity to produce using renewable energy sources with a low carbon footprint.

**Table 2.** Principles defined for the needs and requirements phase.

| | | | |
|---|---|---|---|
| P1. Product development should be based on sustainability principles. | 4.36 | P1. The development of new products should be guided by sustainability principles. | 4.60 |
| P2. Conventional energy sources should be replaced by energy sources with a low impact on the carbon footprint. E.g., hydropower plants, solar panels and wind farms | 4.50 | P2. Conventional energy sources should be replaced by energy sources with a low impact on the carbon footprint or at least an energy audit should be conducted to reduce the energy consumption. | 4.80 |

For the first principle, P1, we did not receive any recommendations by the experts, but for round two, we reformulated the principle to be a bit more specific. Therefore, in the second round, the score was higher than in the first round. In conclusion, we can say that the experts appreciated more the second principle where details were more specific.

For the second principle, one of the participants stated that the energy sources with a low impact on carbon footprint were more expensive, so that was why we added the alternative to be performed at least and an energy audit to reduce the energy consumption. The increase was higher by 0.3, so the panel was more in agreement with a principle where there were two possible options to choose from.

In Figure 5, the expert confidence level is shown for the principles developed in the second phase of the life cycle, when the design of a product is determined. The principles developed at this stage were easily seen to carry more weight in the second round under the experts' considerations.

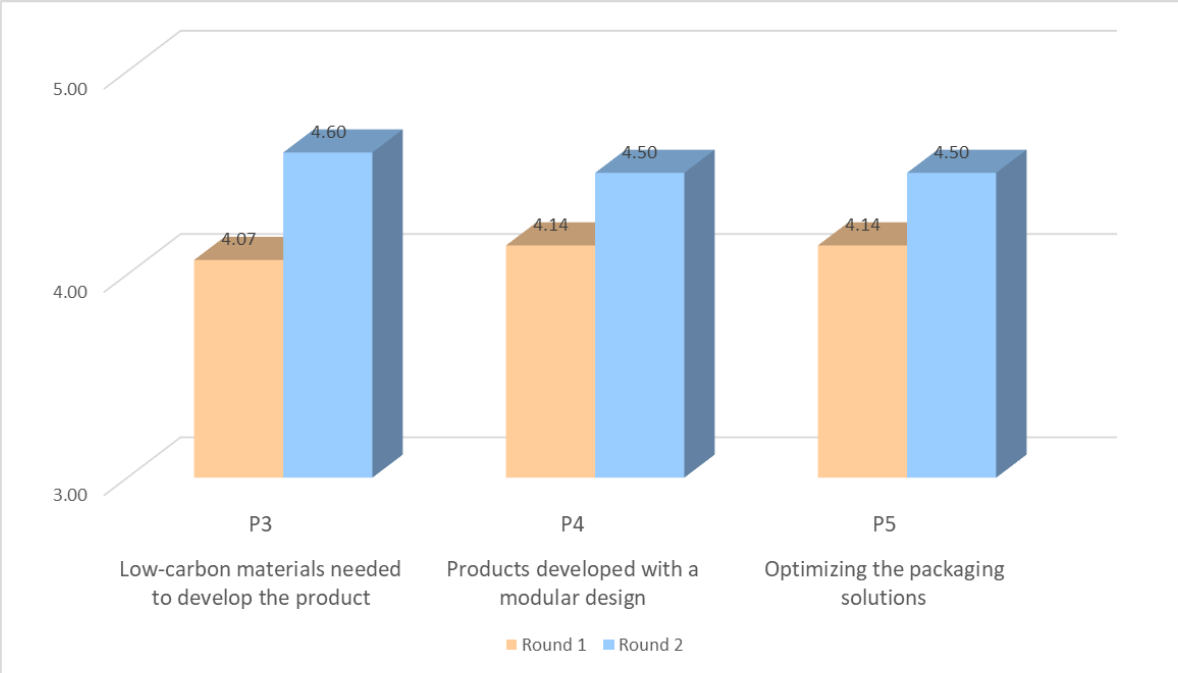


**Figure 5.** Principles defined for product design phase (own research).

At the design phase, in order to achieve a low-carbon product, companies should develop products with materials that are as sustainable as possible and, at the same time, packaging and transport solutions should have a small impact on the carbon footprint.

Table 3 below shows the principles developed for this stage, together with the scores achieved. In addition, the changes employed to each principle as a result of the experts' recommendations are shown after the table.

**Table 3.** Principles defined for product design phase.

| | | | |
|---|---|---|---|
| P3. The carbon footprint of the raw materials required to develop the new product should be as small as possible. Comment: carbon fiber, composite materials, etc. | 4.07 | P3. The carbon footprint of the raw materials required to develop the product should be as small as possible, or at least the carbon footprint of them should be calculated by the supplier. | 4.60 |
| P4. Developers should ensure a modular design of the new product developed. | 4.14 | P4. For a long life cycle product developed, the designers should develop a modular design using, whenever possible, recycled materials, and for short life cycle products, the designers should use recycled materials as much as possible. | 4.50 |
| P5. The new product developed must have a compact design, so that product logistics use less fossil fuels. | 4.14 | P5. After compiling the customer requirements, the developers should optimize and/or standardize the packaging solution for the compact product designed. | 4.50 |

For P3, the only recommendation we received was that it was difficult (from an industry point of view) to meet this requirement, so we added the alternative that at least the carbon footprint should be calculated by the supplier. This resulted in an increase of 0.53 in the acceptability level of the principle. Therefore, this significant increase reflected a considerable improvement for the second-round principle.

For the fourth principle, P4, we received four recommendations from participants, all related to product size, as not all products can support a modular design or have a larger carbon footprint by integrating these modules. Thus, the principle received a second option, related to the lifecycle length for which it was developed, and the score obtained in round two was 4.5, 0.36 higher.

The recommendations for P5 were, firstly, to meet customer requirements and, secondly, that the product could be delivered disassembled to simplify transport. Therefore, the acceptability scores of integrating the principal recommendations in the second round increased by 0.36 to 4.5.

In Figure 6, principles P6 and P7 are shown, having been constructed for the prototype development and prototype testing and validation phases.

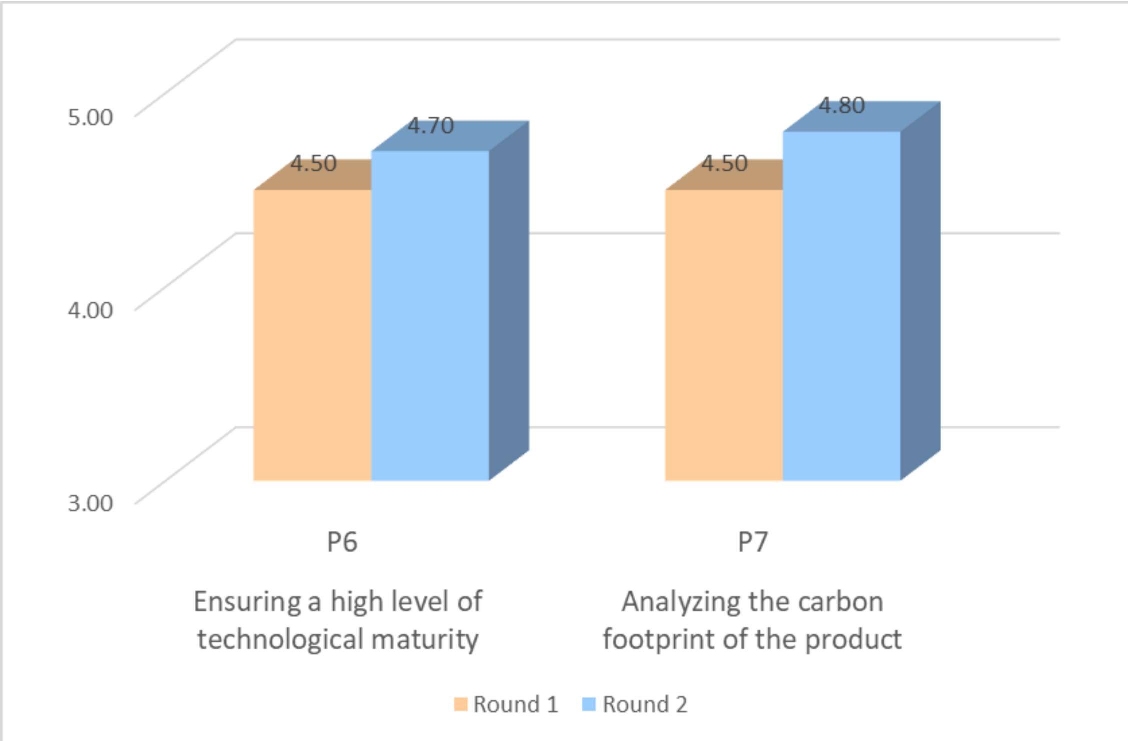


**Figure 6.** Principles defined for the prototype development, testing and validation phases (own research).

At these phases of product development, the developers should think about the technologies needed to develop the product in such a way that they have a low impact on the carbon footprint, and calculate what the carbon footprint impact of the product is over its lifecycle.

The following Table 4 shows the principles constructed for both rounds, together with the scores obtained and the recommendations received.

**Table 4.** Principles defined for the prototype development, testing and validation phases.

| | | | |
|---|---|---|---|
| P6. Developers of new products should ensure a level of technological maturity that reduces $CO_2$ emissions. | 4.50 | P6. New product developers should ensure a high level of technological maturity of the manufacturing processes aimed at reducing $CO_2$ emissions. | 4.70 |
| P7. Companies should perform an analysis of the carbon footprint generated by the product throughout its life cycle. | 4.50 | P7. All the companies, regardless of company size, should perform an analysis of the carbon footprint generated by the product throughout its life cycle or at least an estimation of the $CO_2$ emissions for the products for which an adequate analysis cannot be performed. | 4.80 |

For P6, the improvement recommendations we received were related to increasing the level of technological maturity and the specificity of process types. Therefore, by integrating these recommendations into the principle, the acceptability rating increased from 4.5 to 4.7.

The only comment we received for P7 was that the automotive sector was already requested by UE legislation, so we adjusted the principle for all types of sectors and added an alternative for them to at least determine an estimation of the carbon footprint, if an adequate analysis is not possible. After rephrasing the principle, the acceptability rating increased from 4.5 to 4.8.

In Figure 7, the principles developed for the industrialization and production phases are shown. Thus, the first seven principles were applied in the industrialization phase and P15 in the production phase. It is worth noting the improvement of the experts' opinion on the principles developed in the second round (blue bars).

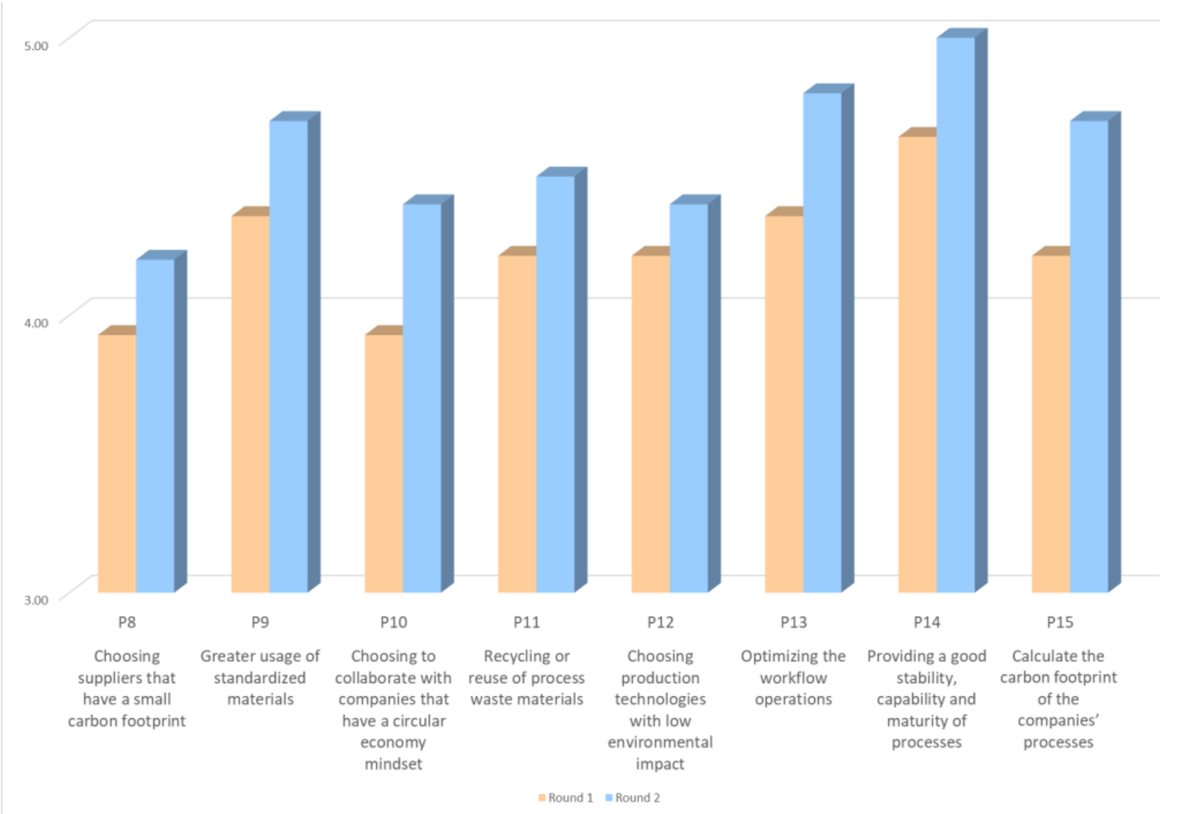


**Figure 7.** Principles defined for the industrialization and production phases (own research).

Table 5 shows the constructed principles together with the scores obtained. Additionally, the recommendations received from the experts for round-one principles were outlined after the table.

As for P8, experts recommended that this was only possible for companies with a high turnover, or that eliminating some suppliers could lead to adding additional production processes that could ultimately increase the carbon footprint. Therefore, from this point of view, we added the alternative of exploring whether the product can be created with other materials whose carbon footprint is smaller. Thus, the acceptability rating increased by 0.27 to 4.20. Usually, scores in round two exceeded 4.5, but 4.2 was not a bad score either.

The recommendations for P9 were related to raw material standardization, which seemed to be a common goal that comes naturally with cost pressures and selecting the cheapest material that could perform the job, while avoiding wasting other costs. The new principle was improved by taking these comments into account and offering two options, either choosing materials with a lower carbon footprint or reducing the amount of materials used. Thus, the score obtained in the second round was 0.34 higher, reaching 4.70.

**Table 5.** Principles defined for the industrialization and production phases.

| | | | |
|---|---|---|---|
| P8. The carbon footprint of raw materials and components should be a criterion for companies in choosing the suppliers. | 3.93 | P8. The list of raw materials required for product development should be based on the carbon footprint of the supplier, and if this is not possible, product developers should explore whether there are alternatives for the list of raw materials whose carbon footprint is lower. | 4.20 |
| P9. The materials required to develop the product should be standardized as much as possible. | 4.36 | P9. A high percentage of the materials needed for product development should be standardized, avoiding as far as possible the production of single parts, where the carbon footprint (and costs) tends to increase, or at least look at how the amount of materials needed can be reduced. | 4.70 |
| P10. Materials needed to manufacture the product should come from companies with a circular economy approach. | 3.93 | P10. The materials required to create the final product should come from companies that have a circular economy mindset or at least an open attitude towards implementing measures to reduce the company's carbon footprint. | 4.40 |
| P11. Materials processed during the manufacturing phase have recycling and/or reuse properties in the EOL phase. | 4.21 | P11. Waste materials left unprocessed during the manufacturing phase should have recycling and/or reuse properties. | 4.50 |
| P12. The technologies used in the production process should be sustainable and generate a minimum carbon footprint. | 4.21 | P12. The product configuration and technologies required to manufacture the product should generate less energy consumption to reduce the carbon footprint, or at least the maintenance of the equipment should be performed properly to ensure a better and long-term use. | 4.40 |
| P13. Production engineers should optimize the workflow of operations required to create the product. | 4.36 | P13. The workflow of the developed product should be optimized to reduce the carbon footprint of the process without compromising efficiency. | 4.80 |
| P14. The organization should be focused on ensuring process stability, capability and maturity. | 4.64 | P14. The organization should focus on providing a good stability, capability and maturity of processes, but also on keeping the scalability of processes under control. | 5.00 |
| P15. Companies should calculate and analyze the carbon footprint of their processes. | 4.21 | P15. Manufacturing companies should calculate and analyze the carbon footprint of their own processes and set targets to reduce it or at least implement measures to achieve a lower carbon footprint. | 4.70 |

The expert panel found P10 to often be difficult to deploy these days when facing an acute shortage of raw materials. However, we improved the principle by offering two alternatives, so from a score of 3.93 we reached a score of 4.40 in the second round. In line with this principle, we also needed to find a way to quantify the circular economy mindset.

Principle P11 was slightly modified, as the first drafting did not give the same perspective we wanted at the outset; therefore, in the second round, the principle was more meaningful. By rephrasing it, we obtained an increase of 0.29 to 4.50.

To increase the expert rating of P12, we offered two options for its implementation, because not all companies can afford to change the equipment used in production, so we decided that proper maintenance to extend the lifetime of the technology was a good alternative. Thereby, we obtained a score increase of 0.19, which was good for an overall acceptance.

For principle P13, the experts' recommendations concerned the purpose of the optimization that was missed in the formulation, and the optimized workflow which should not affect the efficiency of the products. The increase in the score by 0.44 showed a very high acceptability from the panel experts, as the score in the second round was 4.80, which was very close to 5, meaning a total agreement.

The improvement of principle P14 added by the experts in the first round was the scalability of the process, which needed to be kept under control if the business expanded. In the second round, this principle obtained a perfect score of five, which meant that the entire panel of experts fully agreed with this principle.

The comments on principle P15 referred to the limited data available to companies to conduct this kind of analysis; therefore, if this could not be achieved, the second option would be to at least implement low-carbon measures. Offering the second alternative increased the first-round score from 4.21 to 4.70, a significant increase in the concept's acceptability.

In Figure 8, the principles defined for the distribution and sales phases of the product are shown. The first four principles were set for the distribution phase of the product, and the last principle was set for the sales phase.

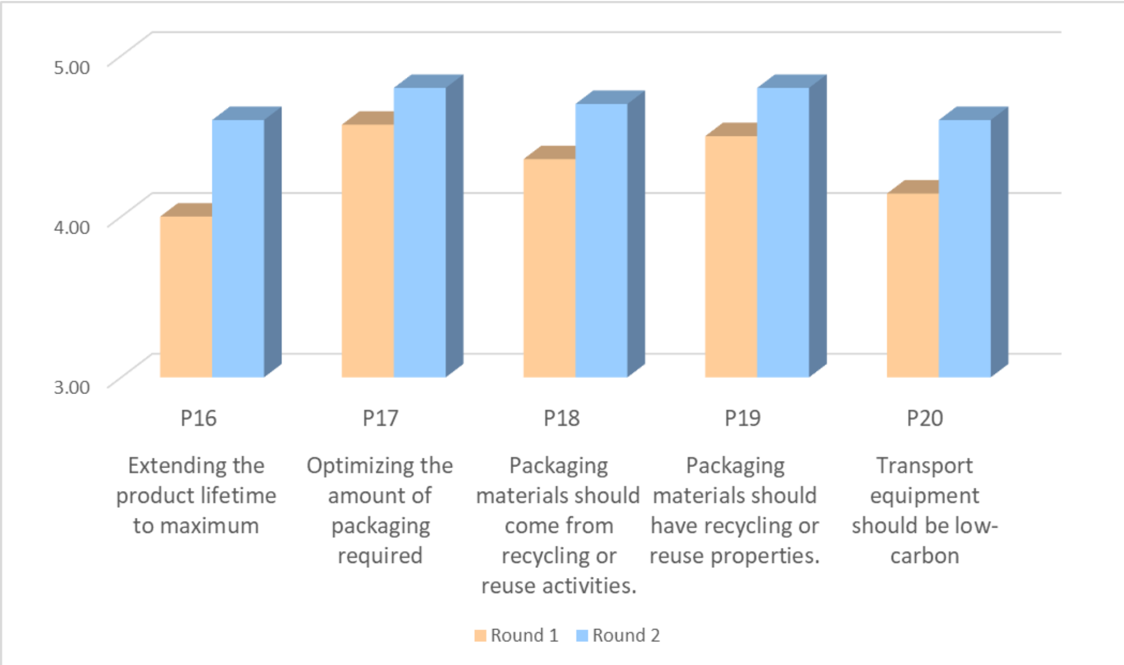


**Figure 8.** Principles defined for the distribution and sales phases (own research).

The principles built into Table 6 referred to increasing the product's lifetime to avoid waste, packaging materials that should not affect the environment and the transport methods that should have a minimum carbon footprint or energy consumption. Additionally, following the table, we showed the experts' recommendations that contributed to the principles' improvement in round two.

Improvements to principle P16 were related to misunderstandings between the term life cycle and usage lifetime, so the principle was rephrased to reflect these observations. After adding these improvements in the second round, the score increased substantially from 4.00 to 4.60.

Regarding principle P17, even though the feedback for it was very good, we decided to define a more specific principle, so that the actions that the organization needed to take were set out more clearly. Therefore, in the second round of the Delphi questionnaire, the degree of desirability of the principle increased from 4.57 to 4.80. Similar to a previous principle, this score was highly embraced by the entire panel of experts.

The recommendation for P18 was to redefine the principle by specifying the amount of packaging material required, which should come mostly from recycling/reuse activities. After rephrasing it, the score in the second round was 4.7, which was 0.34 higher.

For P19, even though the score obtained in the first round was quite high, namely, 4.5, with no recommendations for improvements, in the second round, we redefined it in order to obtain a higher score, in line with the entire set. Hence, an improvement was visible, with the score jumping from 4.5 to 4.8.

**Table 6.** Principles defined for the distribution and sales phases.

| | | | |
|---|---|---|---|
| P16. Product life cycle should last as long as possible. | 4.00 | P16. The lifetime product should last as long as possible, or at least be developed only with recycled or reused materials. | 4.60 |
| P17. The amount of packaging required should be reduced to a minimum. | 4.57 | P17. The amount of packaging required to deliver the new product developed should be reduced to a minimum without compromising the aesthetics or safety of the product. | 4.80 |
| P18. The required packaging should come from recycling and/or reuse. | 4.36 | P18. A high percentage of the packaging required for the product developed should come from recycling and/or reuse. | 4.70 |
| P19. The required packaging should have recycling and/or reuse properties. | 4.50 | P19. The packaging required to deliver the new product developed should also have reusable and/or recyclable properties. | 4.80 |
| P20. The transport inside and outside the facility should be carried out with low-carbon solutions. | 4.14 | P20. The transportation inside and outside the facility should be carried out with low-carbon equipment or at least with a lower consumption of energy or fossil fuels. | 4.60 |

The recommendations for P20 were related to the lack of knowledge about which type of car is more environmentally friendly, and the high prices imposed by transporting products abroad. Instead, we offered participants two options, trying to address the issues they raised. As such, the second option brought an improvement to the principle in the opinion of the expert panel from 4.14 to 4.60 in the second round.

Two other principles were developed for the usage phase of the product, as shown in Figure 9. As with the previous figures, it is easy to observe the improvements that occurred in the experts' opinions between rounds.

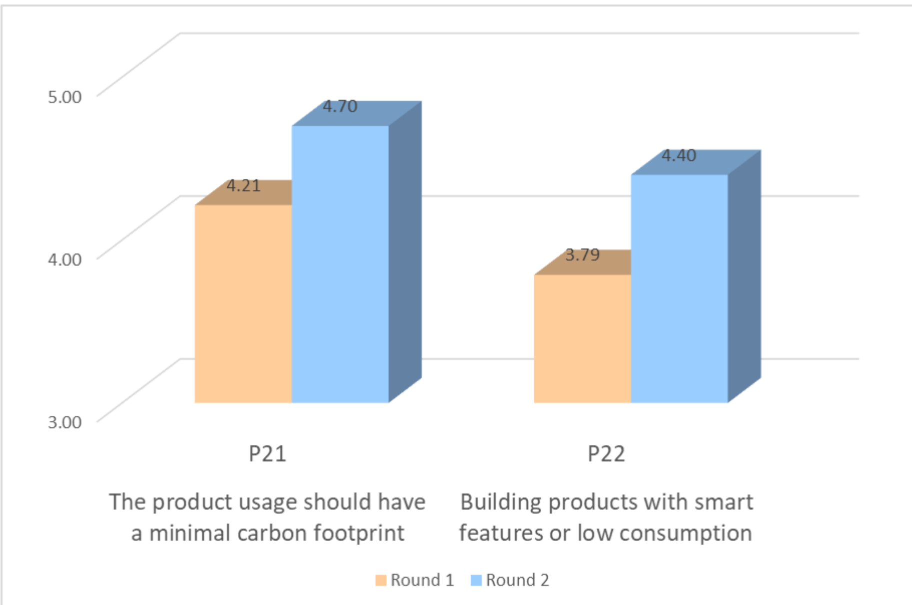


**Figure 9.** Principles defined for the employment phase (own research).

The principles set out in Table 7 refer to the carbon footprint that the product generates in terms of consumption and usage by the customer.

**Table 7.** Principles defined for the employment phase.

| | | | |
|---|---|---|---|
| P21. The use of the new product developed and manufactured should generate a minimum carbon footprint. | 4.21 | P21. During its use phase, the new product developed should leave a minimal carbon footprint. | 4.70 |
| P22. The new product developed should have integrated smart features to reduce its carbon footprint. | 3.79 | P22. The new product developed should have built-in smart features to reduce the carbon footprint, such as auto power-off or stand-by functions, or at least have the lowest consumption of energy, fossil fuels, etc., that can influence the increase in carbon footprint. | 4.40 |

P21 scored 4.21 in the first round, and although all opinions were in agreement or strong agreement with the principle, despite this, there were more in agreement than strong agreement responses. Therefore, in the second round, we redefined the principle to make it easier for everyone to understand and to increase the average score obtained in the first round. Unmistakably, the score increased to 4.70.

Principle P22 was a critical principle that had to be reconsidered given the poor score (3.71 being the lowest score). Therefore, for the second round, the necessary improvements recommended by the experts were related to the fact that not all products could reduce their carbon footprint by integrating smart features, as for some of them the introduction of this feature could become a factor that increases the carbon footprint. In this case, we settled on two alternatives that could address a wider range of products. This brought an upward shift in expert opinion on the principle of 0.61, increasing from 3.79 to 4.40.

The following Figure 10 shows the principles defined for the maintenance phase required for the developed product.

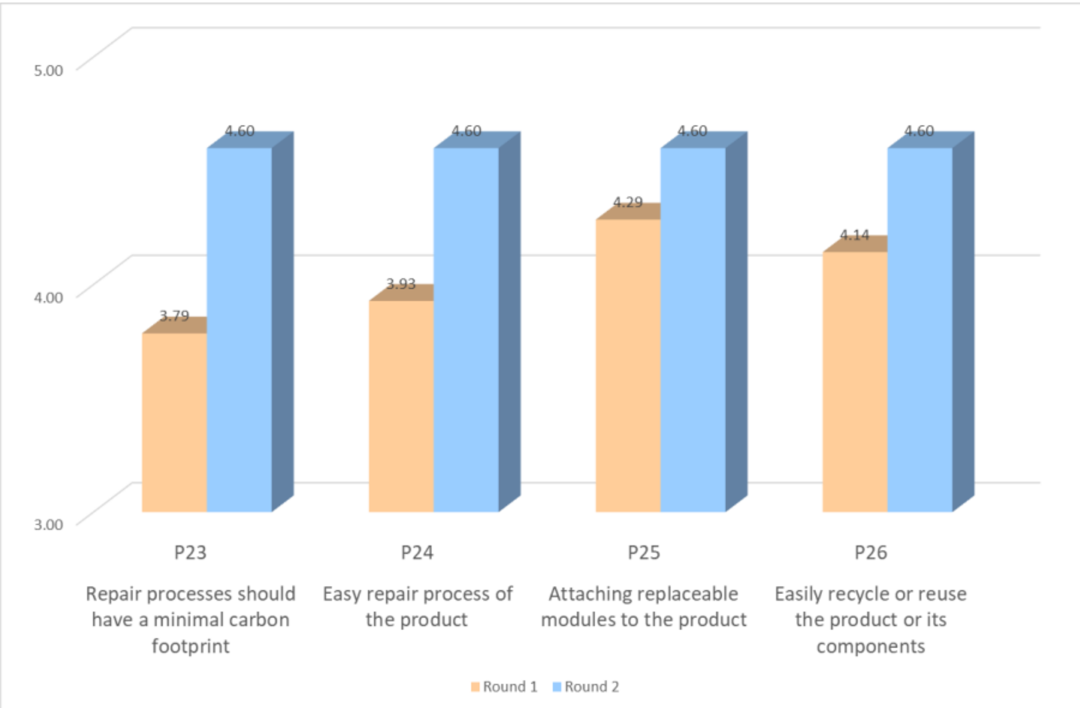


**Figure 10.** Principles defined for the maintenance phase (own research).

Table 8 presents principles to reduce the carbon footprint in the product repair phase, regarding the repair process itself, as well as materials that could be recovered if the product could no longer be repaired.

**Table 8.** Principles defined for the maintenance phase.

| | | | |
|---|---|---|---|
| P23. The carbon footprint generated by the repair process of the developed products should be minimal. | 3.79 | P23. The carbon footprint generated by the repair process of developed products should be lower than that of manufacturing a replacement product. | 4.60 |
| P24. Developers should make products easy to repair, so that some repairs can be performed without specialized intervention. | 3.93 | P24. The repair process should be easy to carry out without specialized intervention, even by the customer themselves, or, if the products are too complex to be carried out in this way, the repair process should have as little impact as possible on the carbon footprint. | 4.60 |
| P25. Replacement of defective components in the product should not affect the life of the product. | 4.29 | P25. The new product developed should have some replaceable product modules to extend the product life. | 4.60 |
| P26. The new product developed should be easy to dismantle and the resulting components should have reuse and/or recycle properties. | 4.14 | P26. The new product developed in the final phase of its life cycle should be easily disassembled by specialized operators, and the resulting components should have reusable or at least recyclable properties. | 4.60 |

In terms of the P23 principle, improvements were undertaken based on a comparison between the manufacturing carbon footprint and the repair carbon footprint, because if the manufacturing process had a lower carbon footprint, then the repair process affected the overall carbon footprint of the product. This was the principle that had the highest jump based on expert opinion of 0.81, from 3.79 to 4.60.

For principle P24, improvements were added because of the complexity of a product, since, if the products were too complex, then repairs could not be performed by customers themselves. Instead, we added an alternative that if this was not possible, at least the repair process should have the least impact on the carbon footprint of the product. Concerning the enhancements suffered by this principle for the second round, the impact was quite significant, growing from 3.93 to 4.60.

In the case of P25, the misunderstandings were due to the fact that not all modules can be replaced, as it is impossible to estimate all failure rates and warranty costs; however, instead, the product can be developed with some replaceable modules that extend the lifetime of the product. With respect to the positive changes that were added, the score increased by 0.31, from 4.29 to 4.60.

The evaluation of P26 in the first round was quite good, but for the second round, we decided that the principle could be defined a bit more, specifically aiming to increase its average score. Thus, the rephrased principle increased by 0.46 to 4.60.

Figure 11 shows the principles constructed for the EOL phase of the product and the level of expert confidence on each principle in both rounds of the Delphi questionnaire.

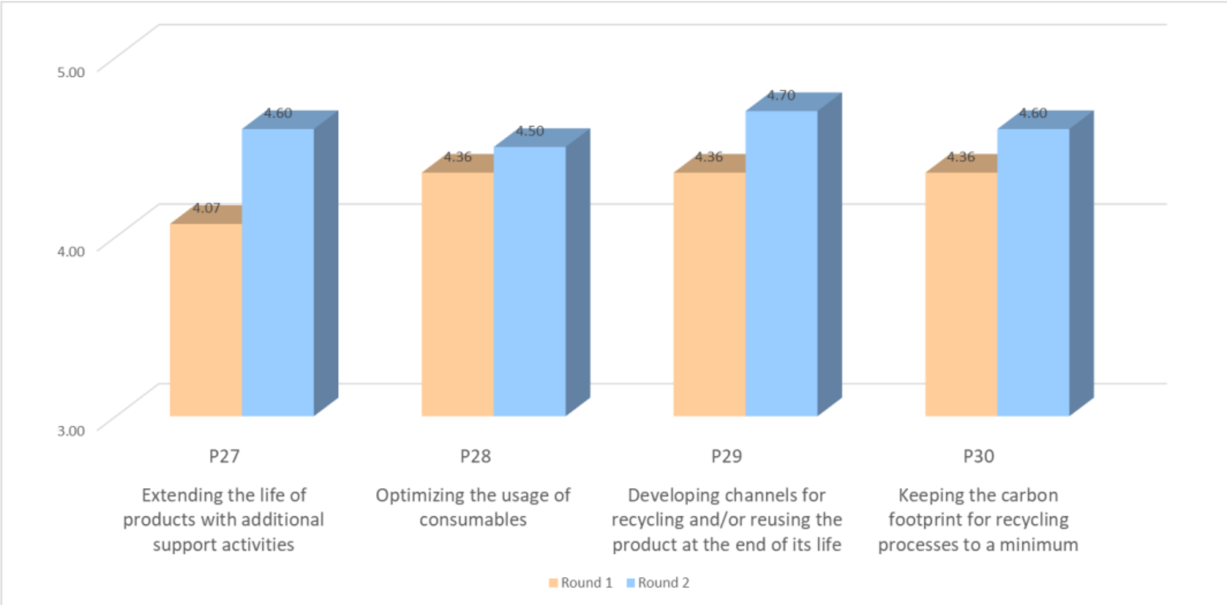


**Figure 11.** Principles defined for the EOL (end-of-life) phase (own research).

The principles set out in Table 9 regarding the EOL phase were constructed with the aim that the product or elements can be reused for the same type of product and/or in other processes, or the materials used for making the product have recycling properties.

**Table 9.** Principles defined for the EOL (end-of-life) phase.

| | | | |
|---|---|---|---|
| P27. Companies should carry out activities that extend the life of new products developed. | 4.07 | P27. Companies should focus on activities that extend the life of new products developed or, if this is not economically feasible, the product should be completely recycled or reused to create new products. | 4.60 |
| P28. Consumables for new products developed should maximize use and minimize the carbon footprint.E.g., the blade of a piece of equipment should be square so that changing the position of the knife allows three more uses. | 4.36 | P28. The use of consumables for new products developed should be optimized so that their consumption is maximized, thereby reducing waste and carbon footprint. | 4.50 |
| P29. The companies should create an efficient communication channel with the customer so that, during EOL, the product reaches the manufacturer or a collaborator who ensures low-carbon recycling and/or reuse. | 4.36 | P29. The companies should create an efficient communication channel with the customer, so that during the entire life cycle, the product reaches the manufacturer or a collaborator who ensures low-carbon recycling and/or reuse. | 4.70 |
| P30. The carbon footprint of product recycling processes should be kept to a minimum. | 4.36 | P30. The carbon footprint of recycling processes should not be higher than the carbon footprint of manufacturing processes or, if this is not possible, at least recycling processes should be optimized so that the carbon footprint is as small as possible. | 4.60 |

The recommendations for principle P27 were related to the lifetime of a product for which there is not always a clear market need in the foreseeable future and to the rate of technological development, which, in most cases, becomes much more efficient than the product developed, which tends to become inefficient after the projected lifetime. Therefore, in order to comply with this, if it is not feasible for the company to extend the lifetime of the developed products, they should only use recycled or reused materials to develop the product. This alternative increased the experts' opinions from 4.07 to 4.60.

For the last three principles, the experts did not add any comments, so the changes that were conducted to these principles were the result of the previous experience of the experts' approaches. Thus, in the second round, their insight into these principles improved. Therefore, the expert confidence level for P28 jumped to 4.50 from 4.36, P29 jumped to 4.70 with an increase of 0.34 and for P30, the increase reached 4.60 from 4.36.

## 6. Discussion of the Results

By analyzing the current literature, one can observe that the options and guidelines for developing products with low environmental impact and diminished carbon footprint are rather sparce. Similarly, companies are working toward this goal, as has been evidenced in the past five years in the automotive industry; however, the large-scale product development of this type of product for mass manufacturing is not yet mainstream. Even for this industry, which is at the focus of policies and investment for carbon dioxide reduction, alongside the energy sector, there is a large number of unknowns and contradictory information and approaches that would take time to clear up [25,26]. In the case of the manufactured goods analyzed in this paper, there were many considerations that affected the potential success of low-carbon design approaches, such as regulations [27], new technologies [28] and product demand [29].

During the research, we observed that the experts considered all the principles to be valuable for developing new products in a low-carbon manner, which meant that these guidelines were a good starting point for delivering sustainable products that meet customer expectations. Additionally, the most valuable principles defined were found in the following phases of the product lifecycle:

- The principles defined for the industrialization phase (seven guidelines with a high degree of agreement—a score above 4 out of 5, and four of these with a score above 4.5);
- The identification of customer needs and requirements (two principles with a high degree above 4.5, and one of them above 4.75);
- The prototype testing and validation phase (one principle with a high degree above 4.75);
- The distribution phase (four principles with a high degree of agreement—a score above 4.5 out of 5, and two of them above 4.75).

The principles for these phases related to the process stability, capacity and maturity, the optimization of workflow operations, use of renewable energy sources, analysis of the product's carbon footprint and optimization and recyclability of packaging materials. These were the principles that were most welcomed by industry experts.

We agreed that the industrialization phase is considered to be of great relevance to reduce the carbon footprint, given the major importance of this phase in the whole life cycle of a product. At this phase, the greatest reduction in carbon emissions can be decided, as the way the new product is produced has a major influence on the amount of emissions generated by the product. Therefore, it is essential that the principles developed in the proposed model are embraced by companies, as it is one of the phases in which a significant part of the manufacturing emissions can be avoided.

It is, therefore, also necessary to be aware of the parameters that customers want for the new product developed, and how these parameters can take physical form in a sustainable manner. Moreover, ensuring that the new product developed meets all the customer's requirements and needs goes along with the sustainability requirements.

After defining the requirements that the product had to fulfil, the testing and validation phase also played an important role in deciding whether the product could fulfil all the requirements in a sustainable way.

The distribution phase also had a high share due to the large amount of $CO_2$ emissions emitted by the transport sector. There is currently a lot of discussion on how to make this sector more sustainable, so finding a way to fully optimize this phase could have a major impact on the product's carbon footprint.

In conclusion, the approaches proposed constituted a practical approach to implementing a special case of the design for sustainability model in the product development and design process, which we consider to be most adequate when pursuing a carbon emission reduction as a goal, and could be labeled as a design for low-carbon products. The content of this framework was formulated in line with the best practices in the field of design for X [30–32], and could contribute to making low-carbon products a mainstream output of the manufacturing sector [33], thus, acknowledging the changes in customer predispositions.

## 7. Summary

Our proposed set of principles was developed as a holistic response to these challenges, and it integrated insights from product designers and companies, form the authors' own experiences in the manufacturing industry and, through the Delphi validation process, from experts in the field. These principles corresponded to an extended understanding of the key environmental factors for product success, ranging from material substitution to supply chain networking.

In our approach, we tried to combined research regarding the conceptual basis of product design with innovation in terms of creative guiding principles for companies that seek to transition to a low-carbon economy in a quick and relatively painless manner. There is no avoiding the effort required for this (funding skills and know-how, cultural changes and behavioral changes, both within the companies and for their customers), but we believe that there are ways in which this effort can be properly managed.

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